The Standard Model and Its Problems

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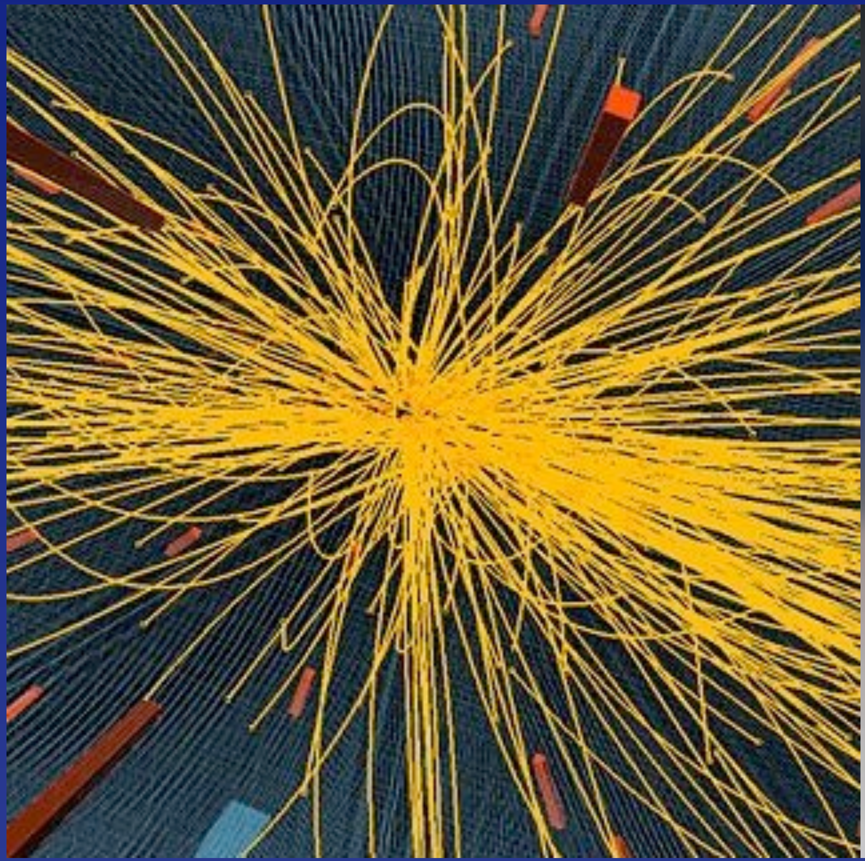


Philosophy of the Standard Model · Maria in der Aue · March 2011

Two New Laws of Nature

Electroweak Theory

+

Quantum Chromodynamics

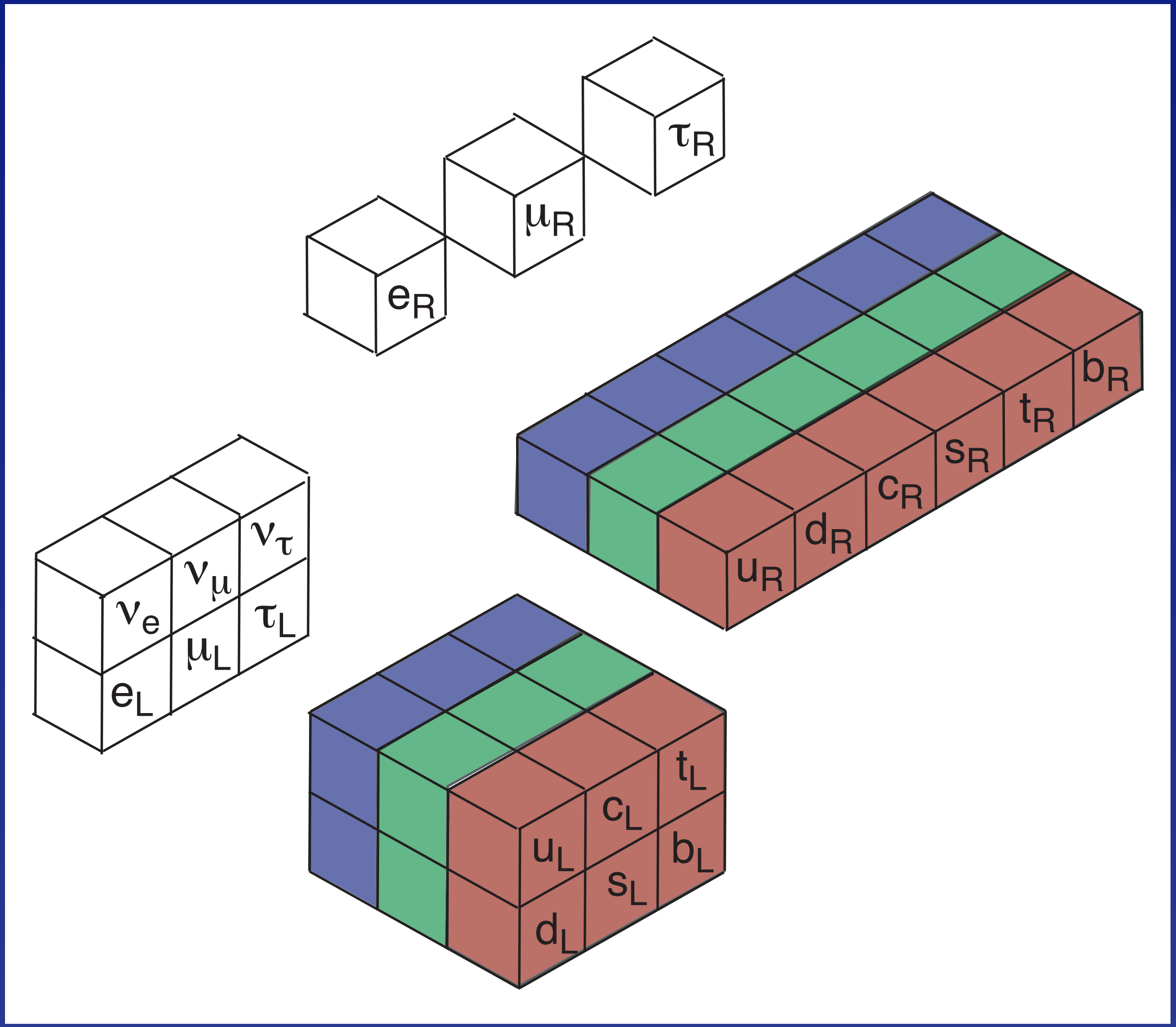
+

Quarks & leptons as fundamental constituents

Standard Model of Particle Physics

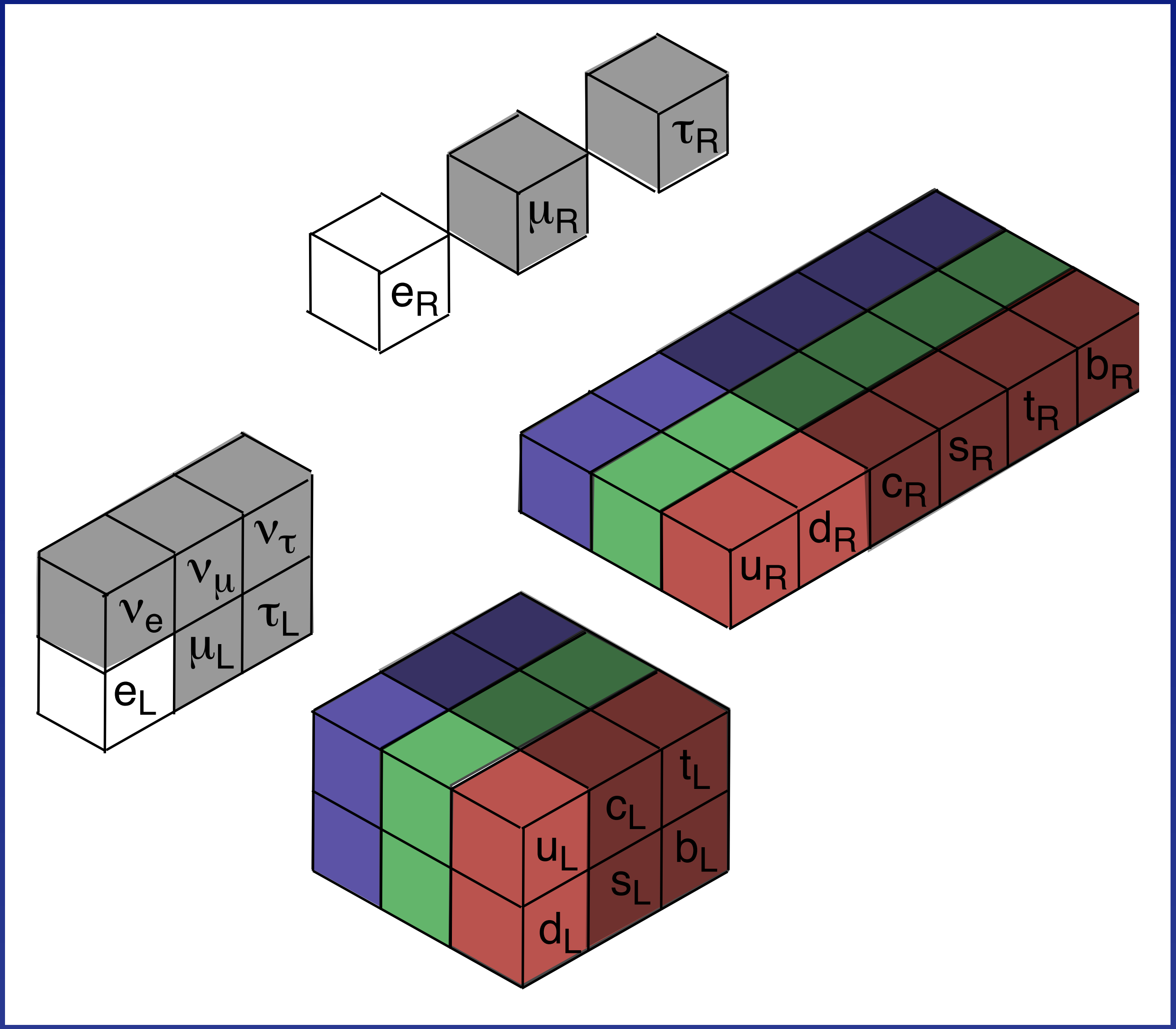
Our Picture of Matter

Pointlike ($r \leq 10^{-18}$ m) *quarks* and *leptons*



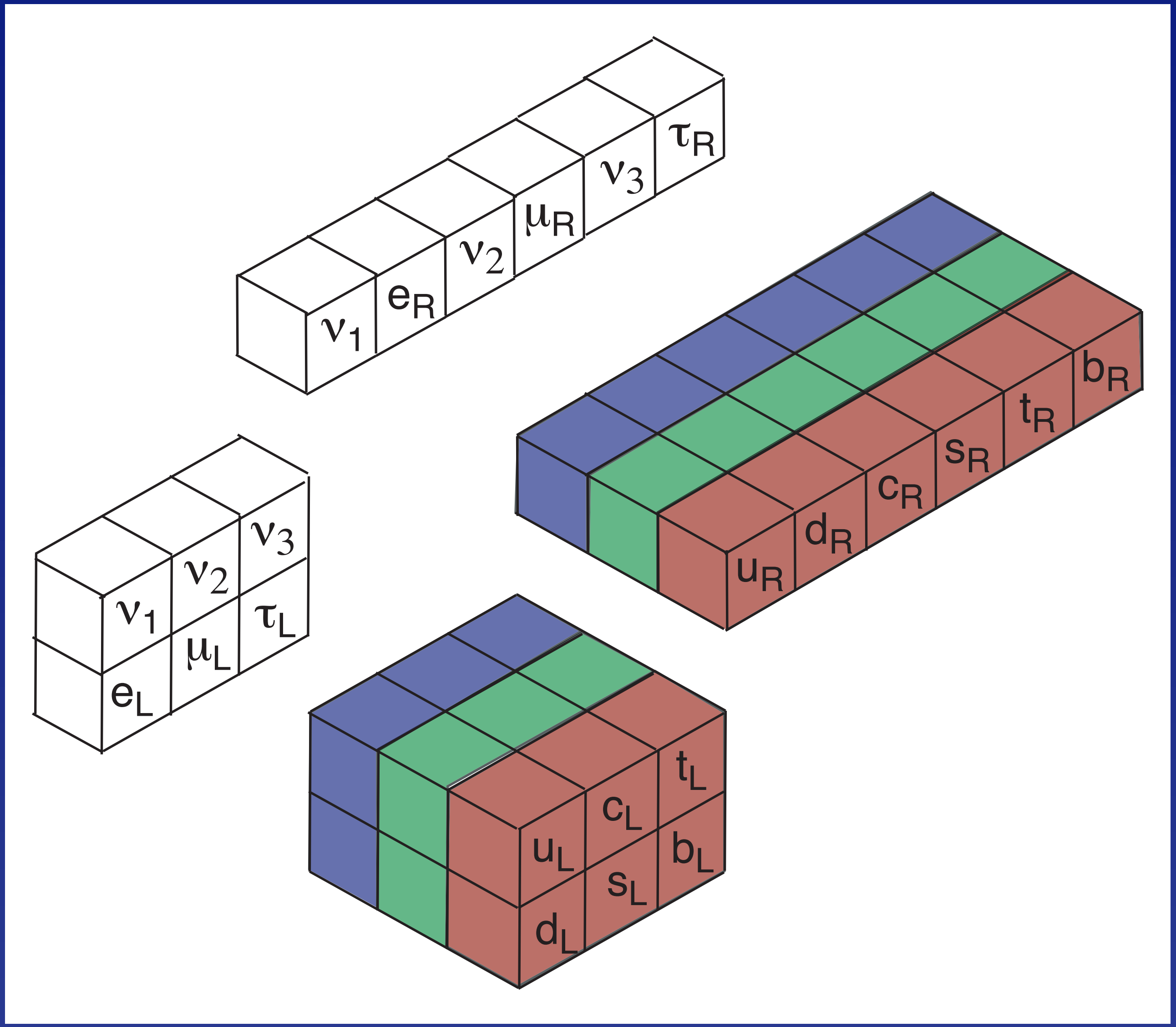
Our Picture of Matter

Pointlike ($r \leq 10^{-18}$ m) *quarks* and *leptons*



Our Picture of Matter

Pointlike ($r \leq 10^{-18}$ m) *quarks* and *leptons*



Interactions: $\mathsf{SU(3)_c \otimes SU(2)_L \otimes U(1)_Y}$ gauge symmetries

8 gluons $\cdot$ $W^{\pm} \cdot Z^0 \cdot \gamma$

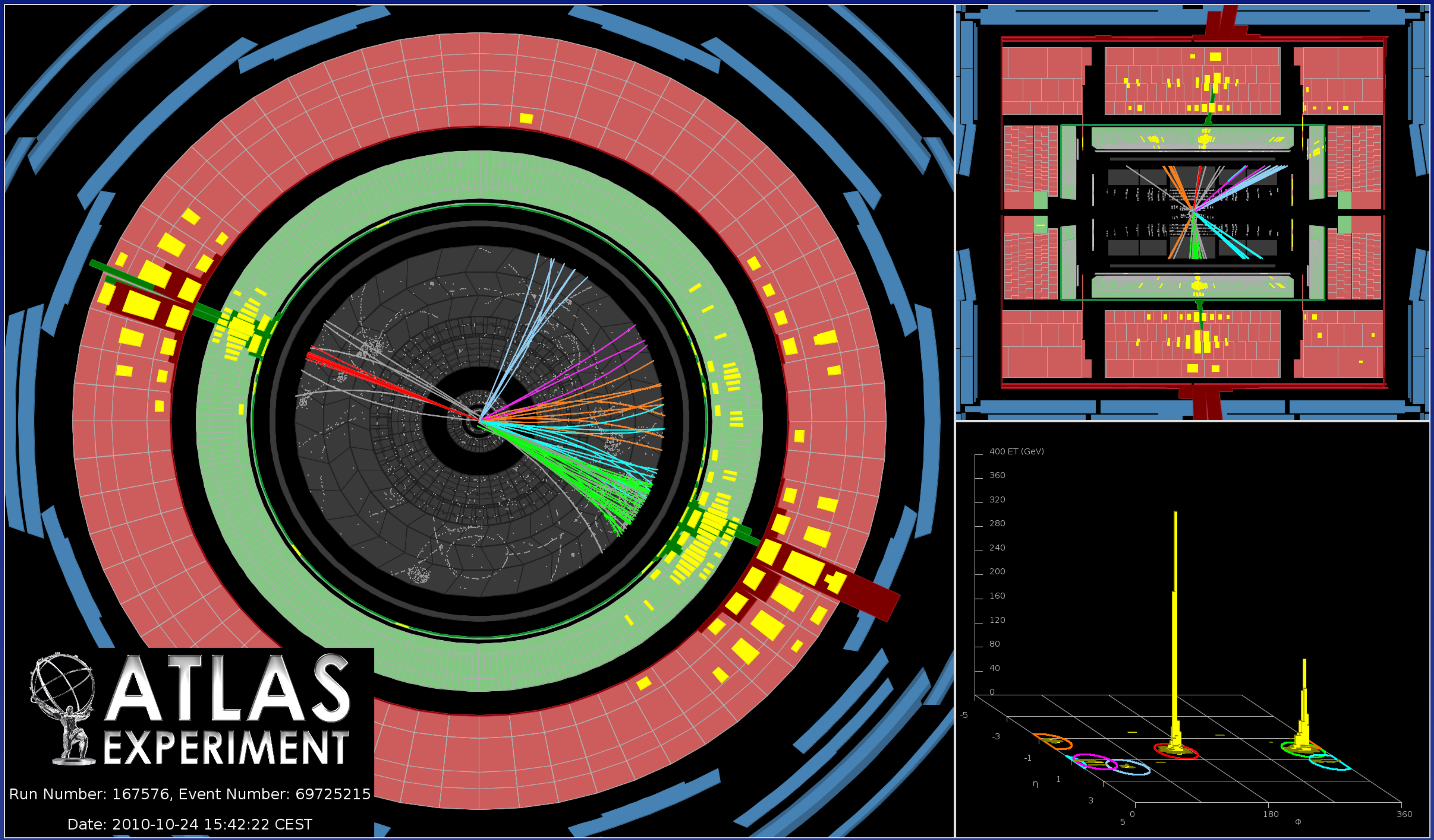
Gravitation mostly set aside

Highly idealized

Many tensions,
puzzles,
outstanding questions

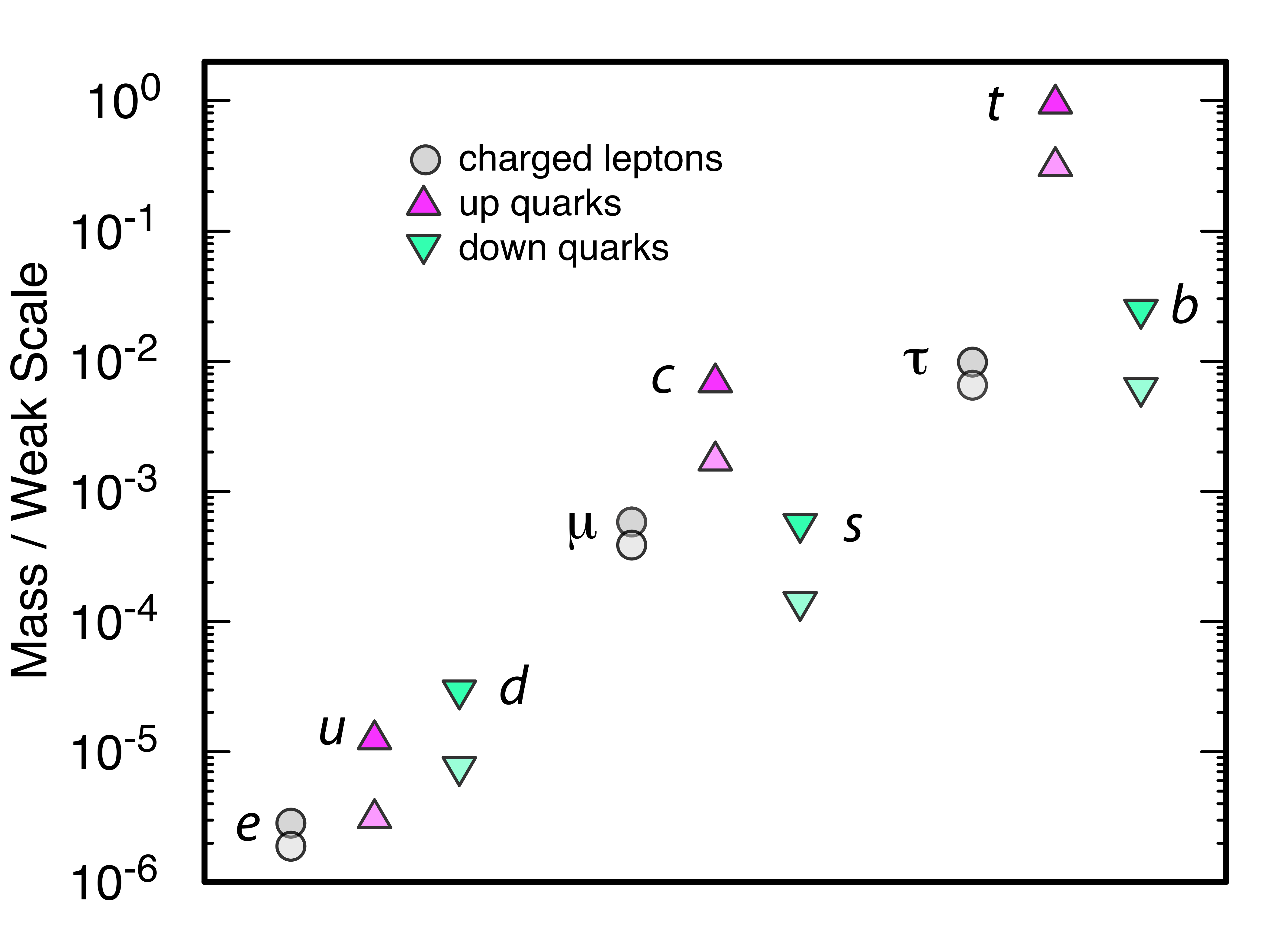
The World's Most Powerful Microscopes

nanonanophysics



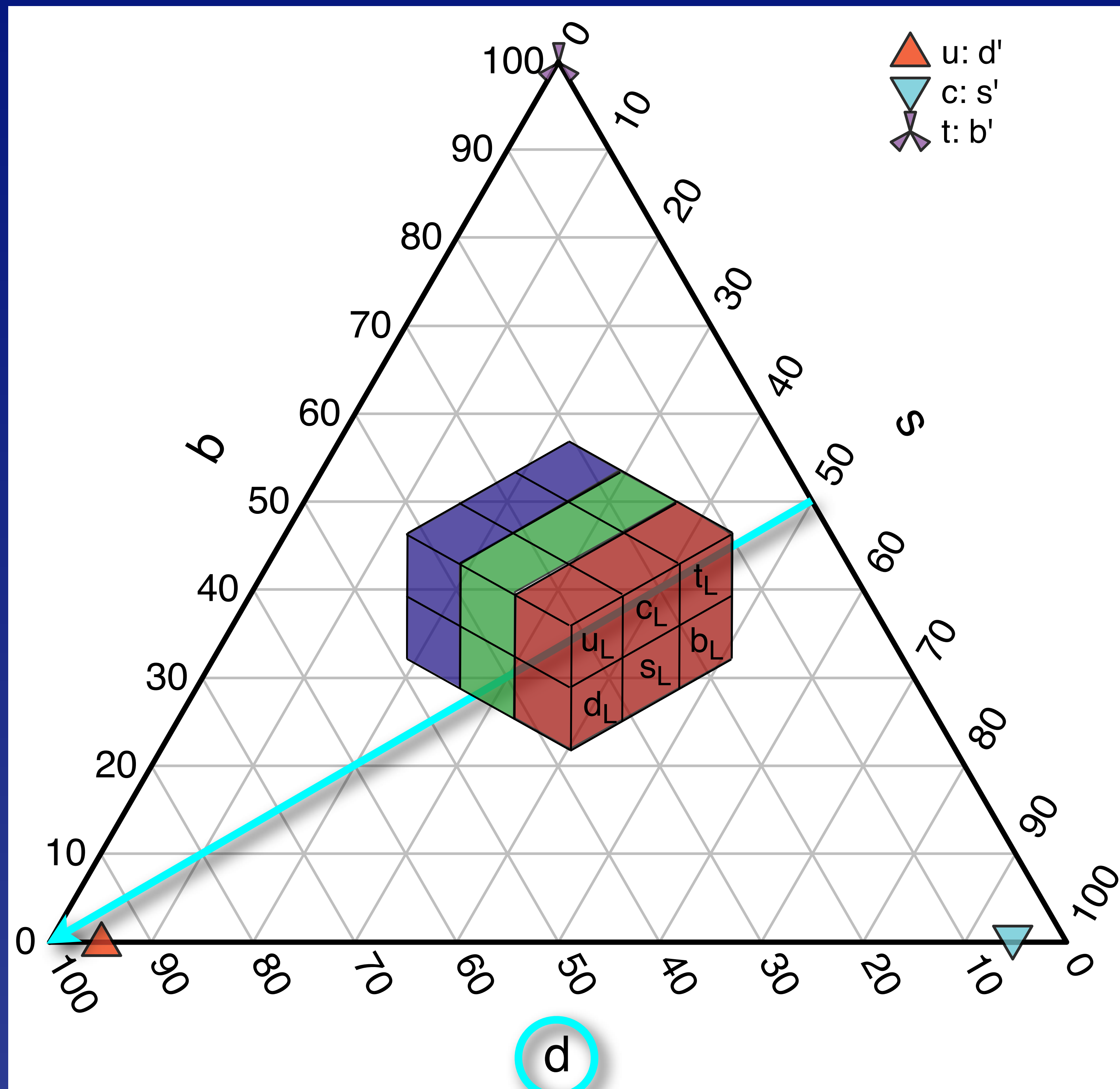
Transverse momenta: 1.3 TeV + 1.2 TeV

Fermion Masses



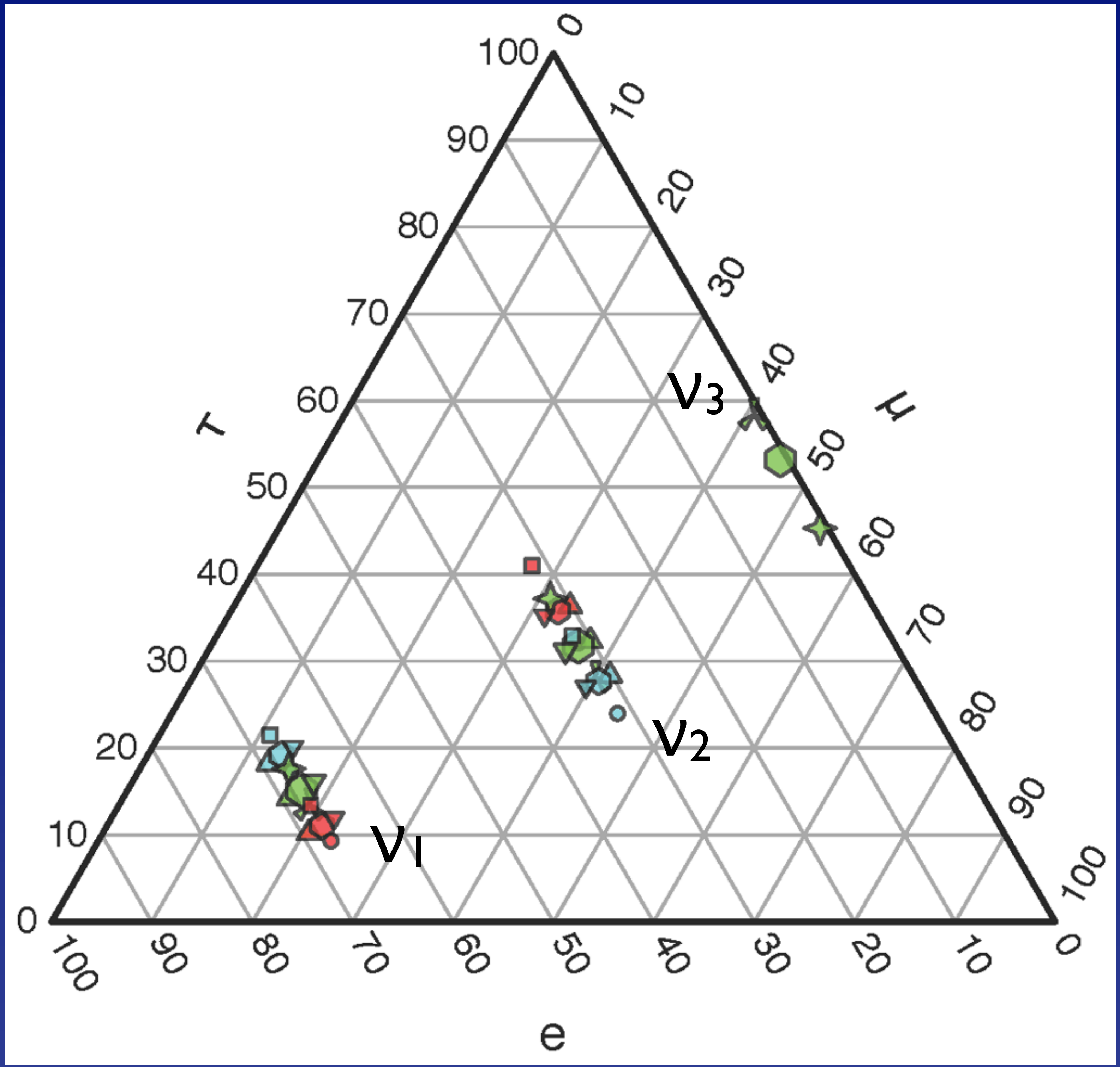
Running mass $m(m)$ … $m(U)$

Quark family patterns: *generations*

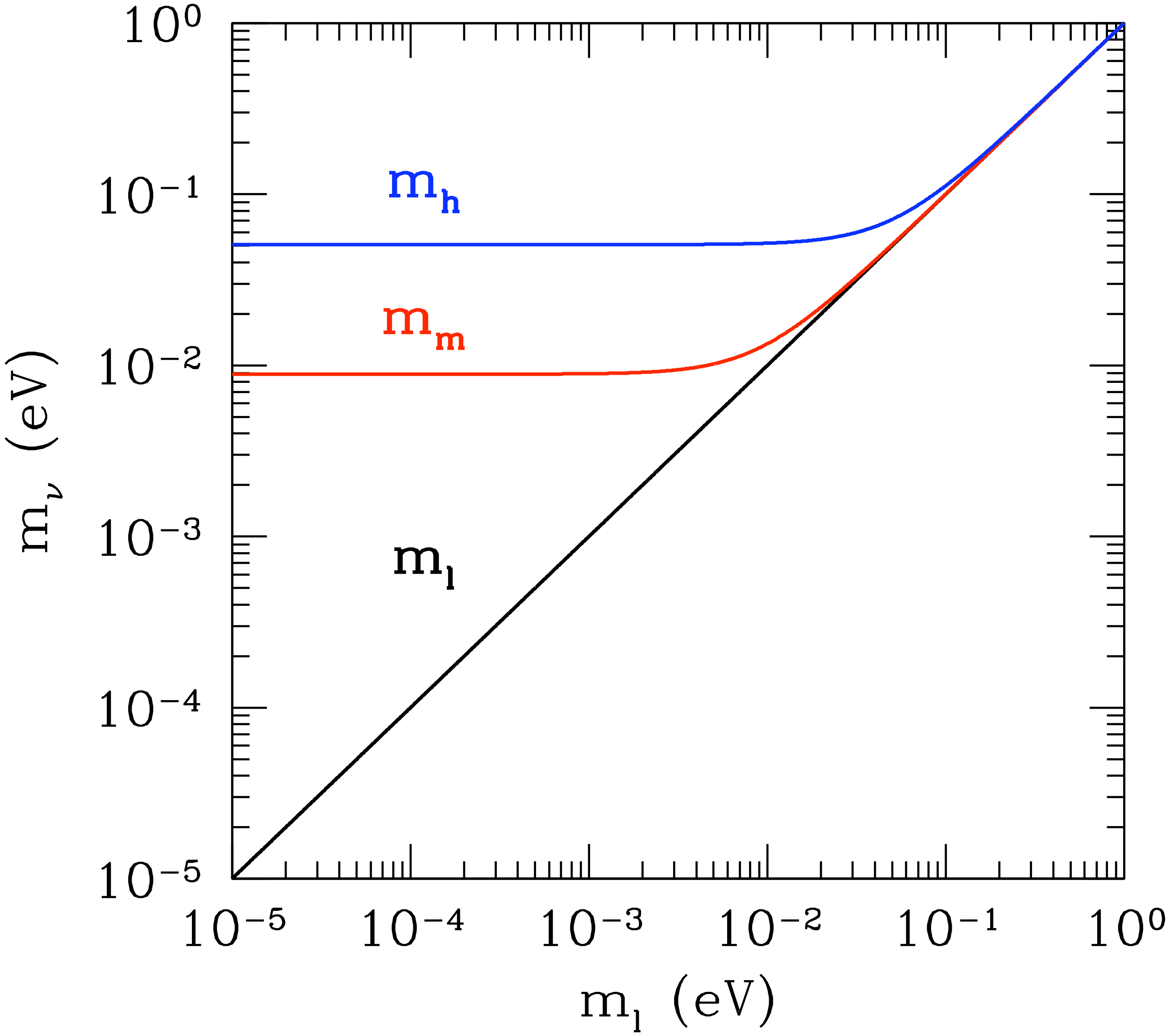


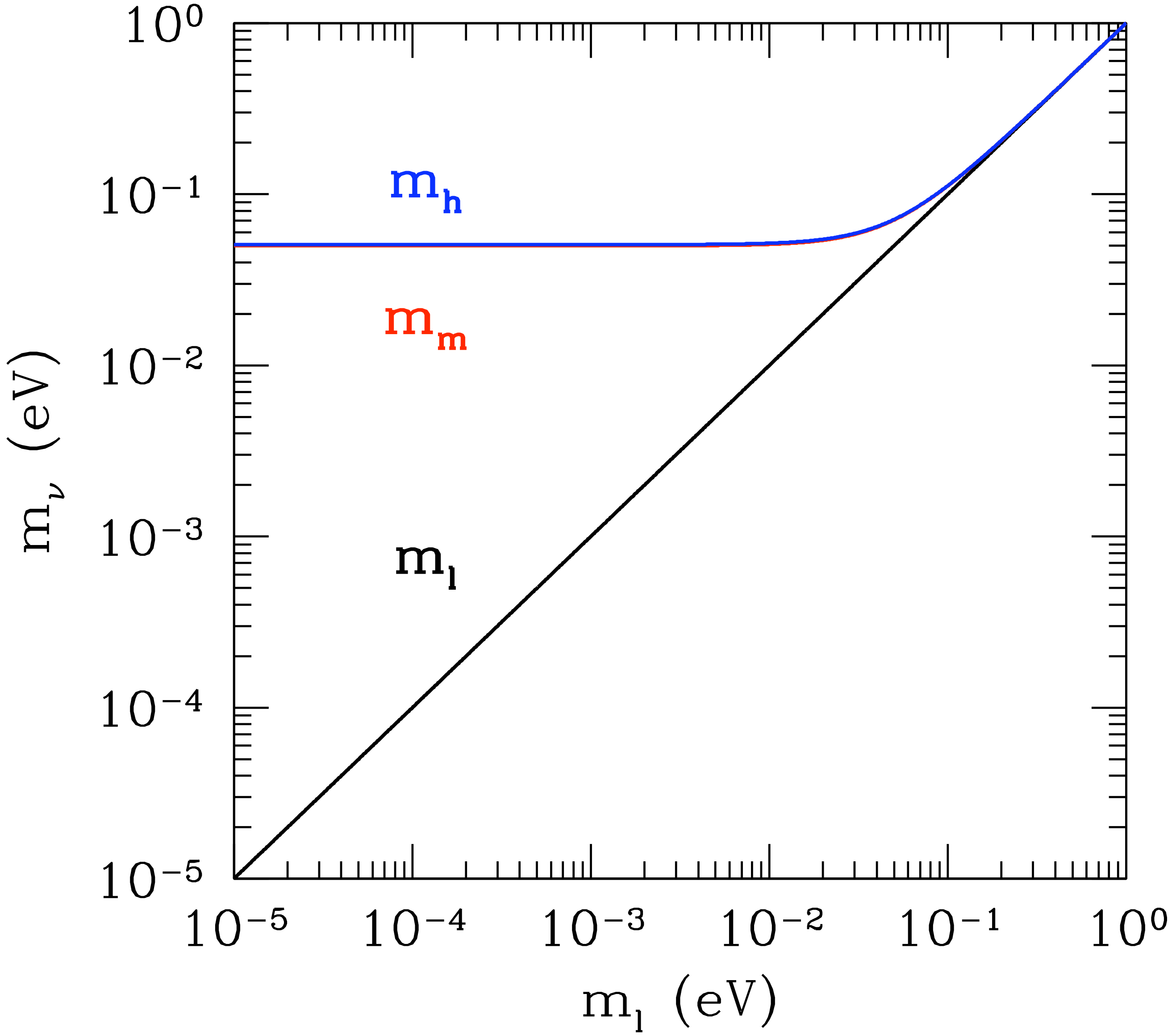
Veltman: Higgs boson knows something we don't know!

Neutrino family patterns



Neutrino Masses

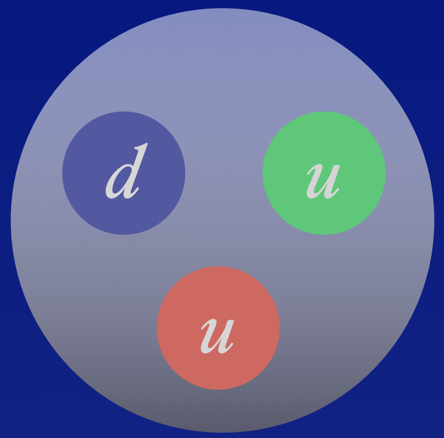


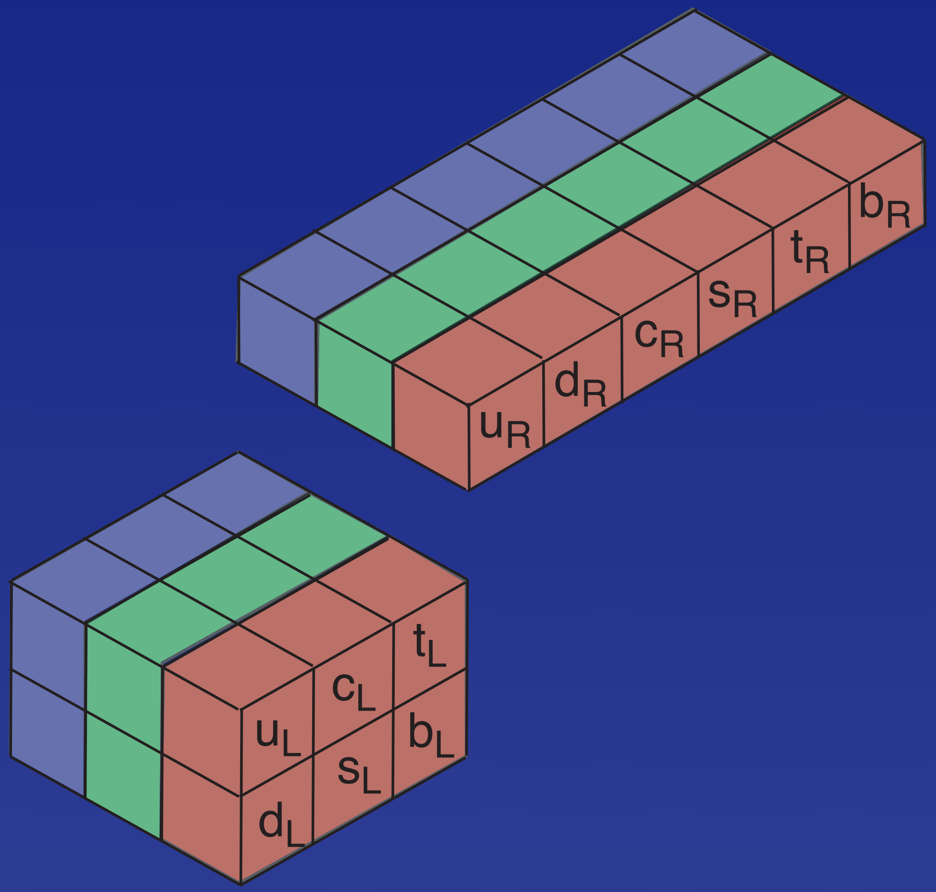


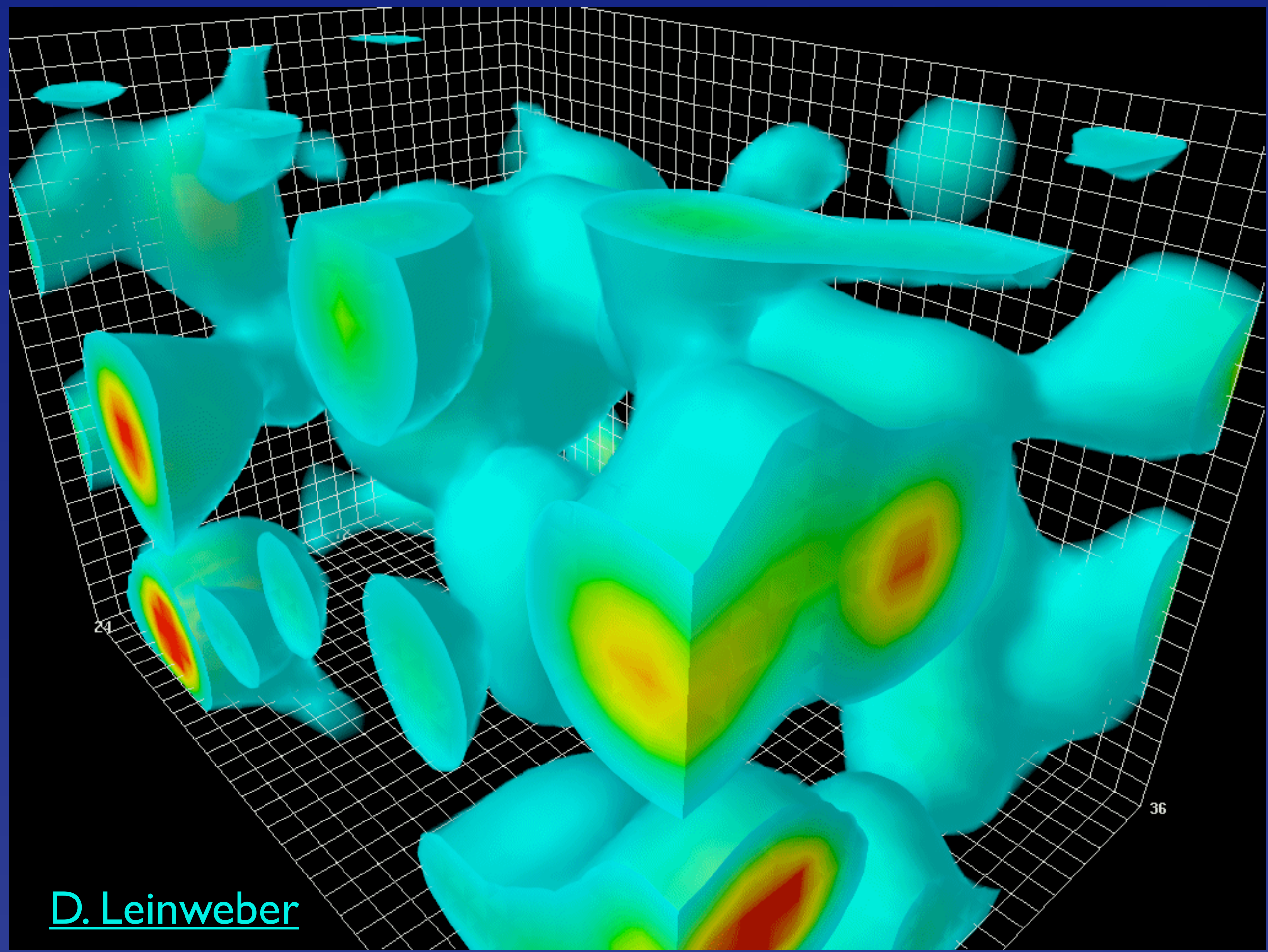
New Law of Nature #1

Quantum chromodynamics (QCD):
color symmetry among quarks
red · green · blue

gluons







Quantum Chromodynamics

Dynamical basis for quark model

Gluons (vector force particles) mediate interactions among the quarks and experience strong interactions.

Contrast *photons*, which mediate interactions among charged particles, not among themselves.

Quark, gluon interactions $\Rrightarrow$ nuclear forces

Quantum Chromodynamics

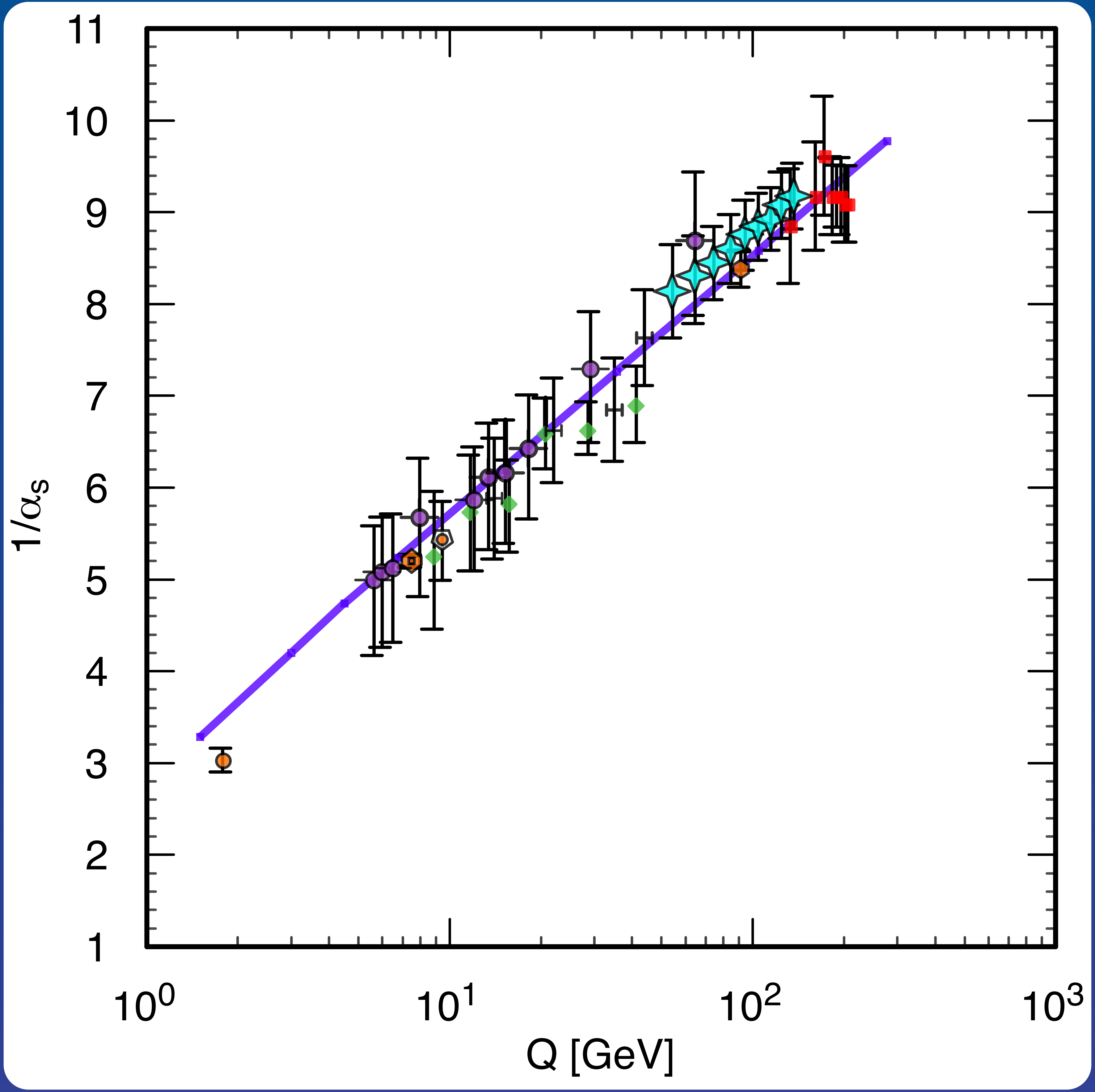
Asymptotically free theory

Many successes in perturbation theory to 1 TeV

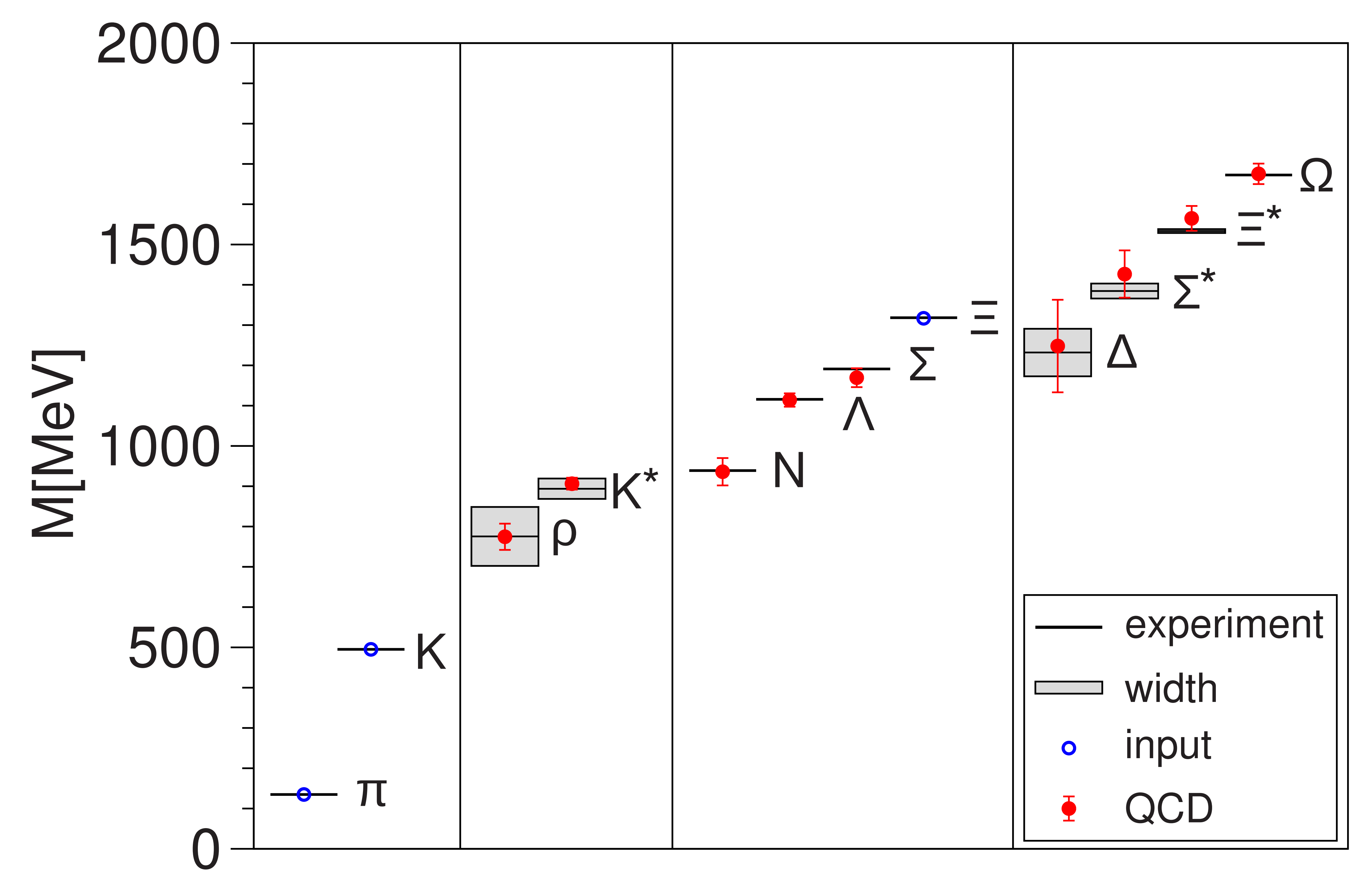
Growing understanding: nonperturbative regime
Quarks & gluons confined: evidence, no proof

No structural defects, but *strong CP problem*

Evolution of the strong coupling “constant”

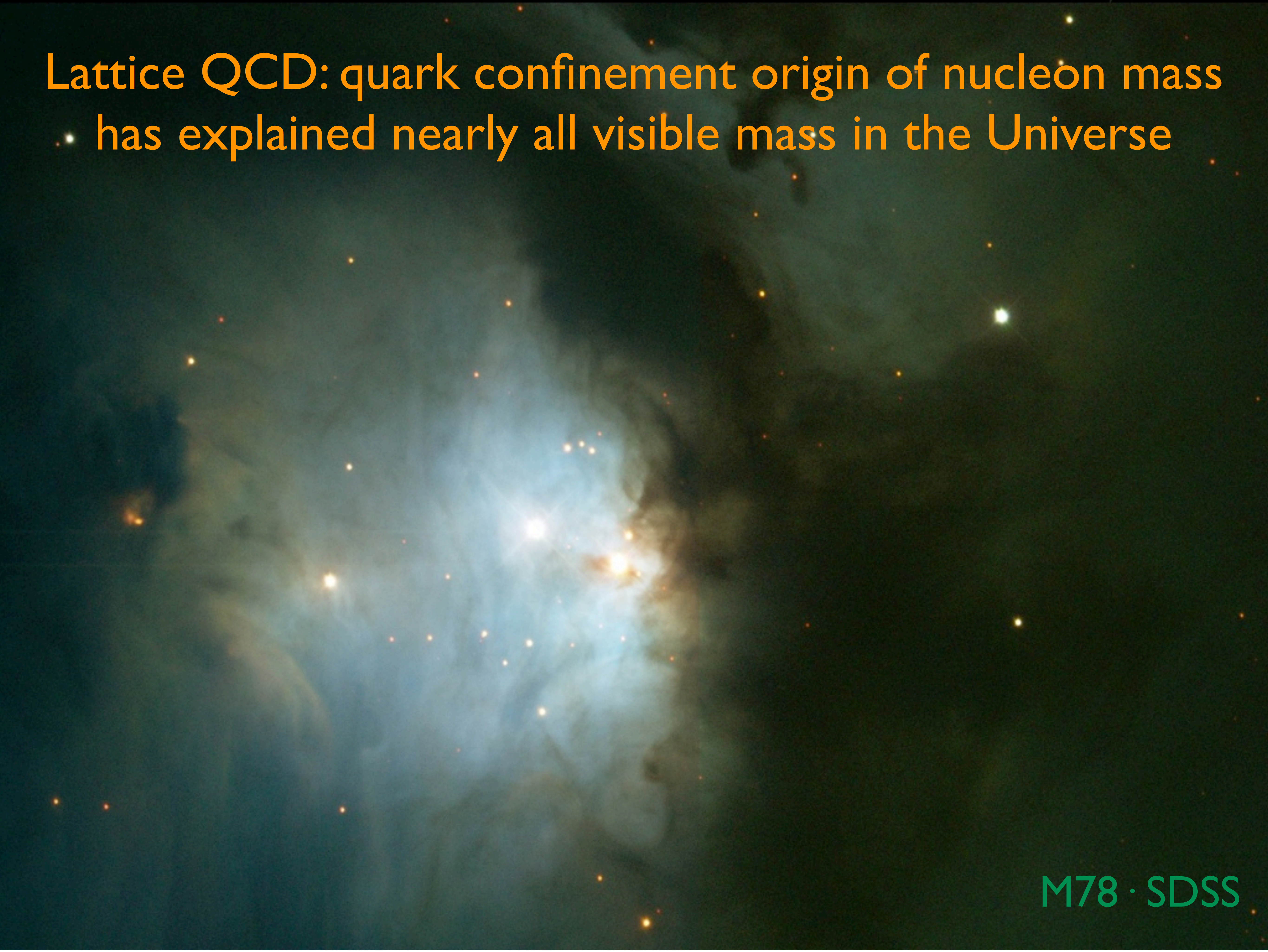


Light hadron spectrum with dynamical fermions



BMW

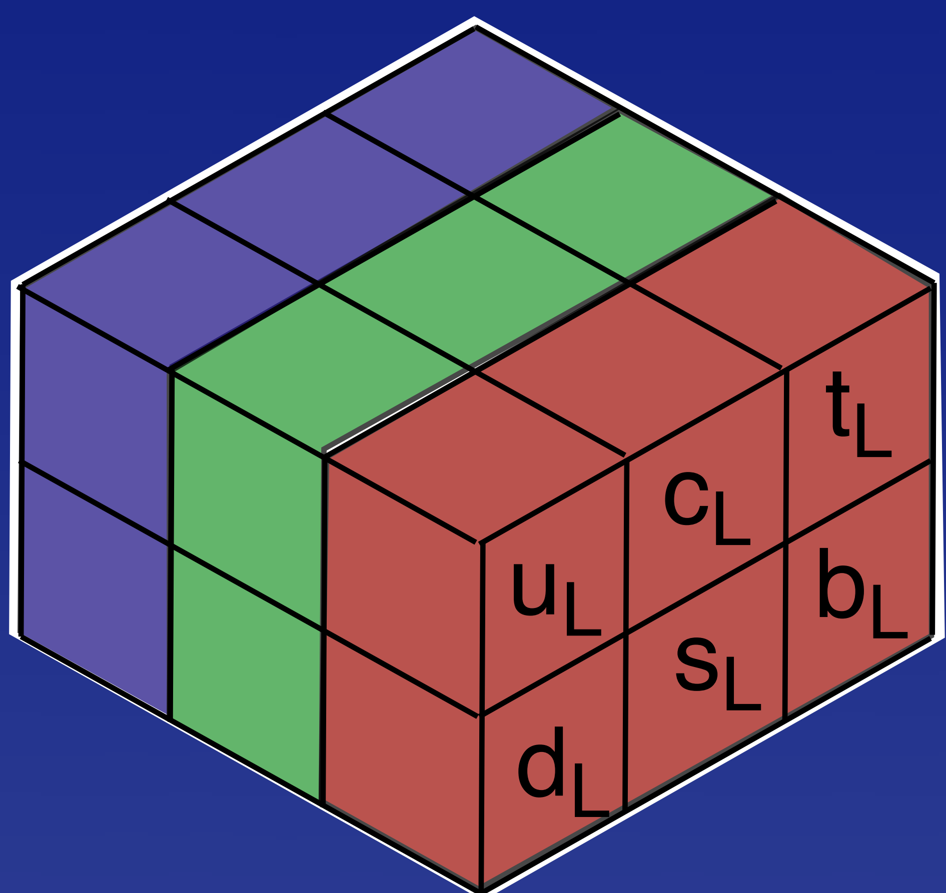
Lattice QCD: quark confinement origin of nucleon mass has explained nearly all visible mass in the Universe

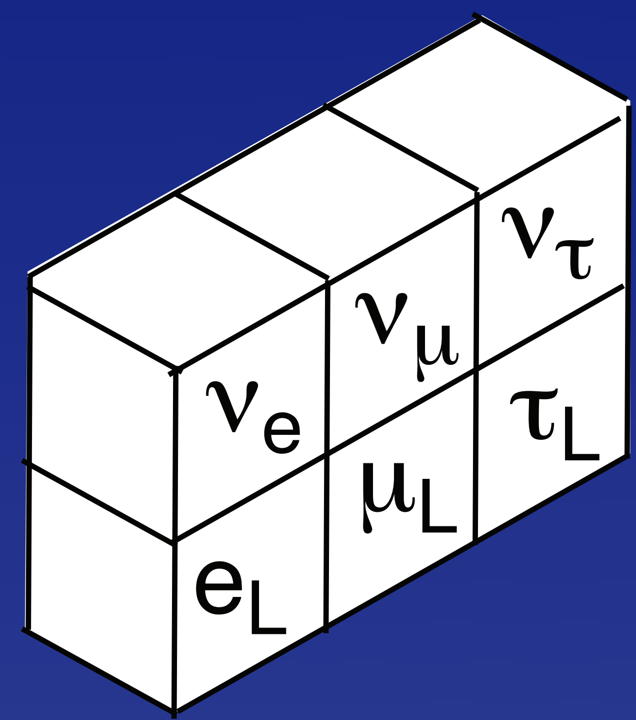


New Law of Nature #2

Electroweak theory:
family symmetry
u ↔ d ; ν ↔ e ; …

weak bosons (W^+, W^-, Z^0) + photon





Electroweak Theory

To good approximation …

3-generation $V\!-\!A$

Flavor-changing neutral currents suppressed

Quark mixing matrix describes CP violation

Gauge symmetry validated in $e^+e^- \to W^+W^-$

Tested as quantum field theory at per-mille level

Weak interactions, electromagnetism seem so different …

Weak	Electromagnetic
range: 1% proton size	infinite range
W: 90 × proton mass	massless photon

How can they share a common origin (symmetry)?

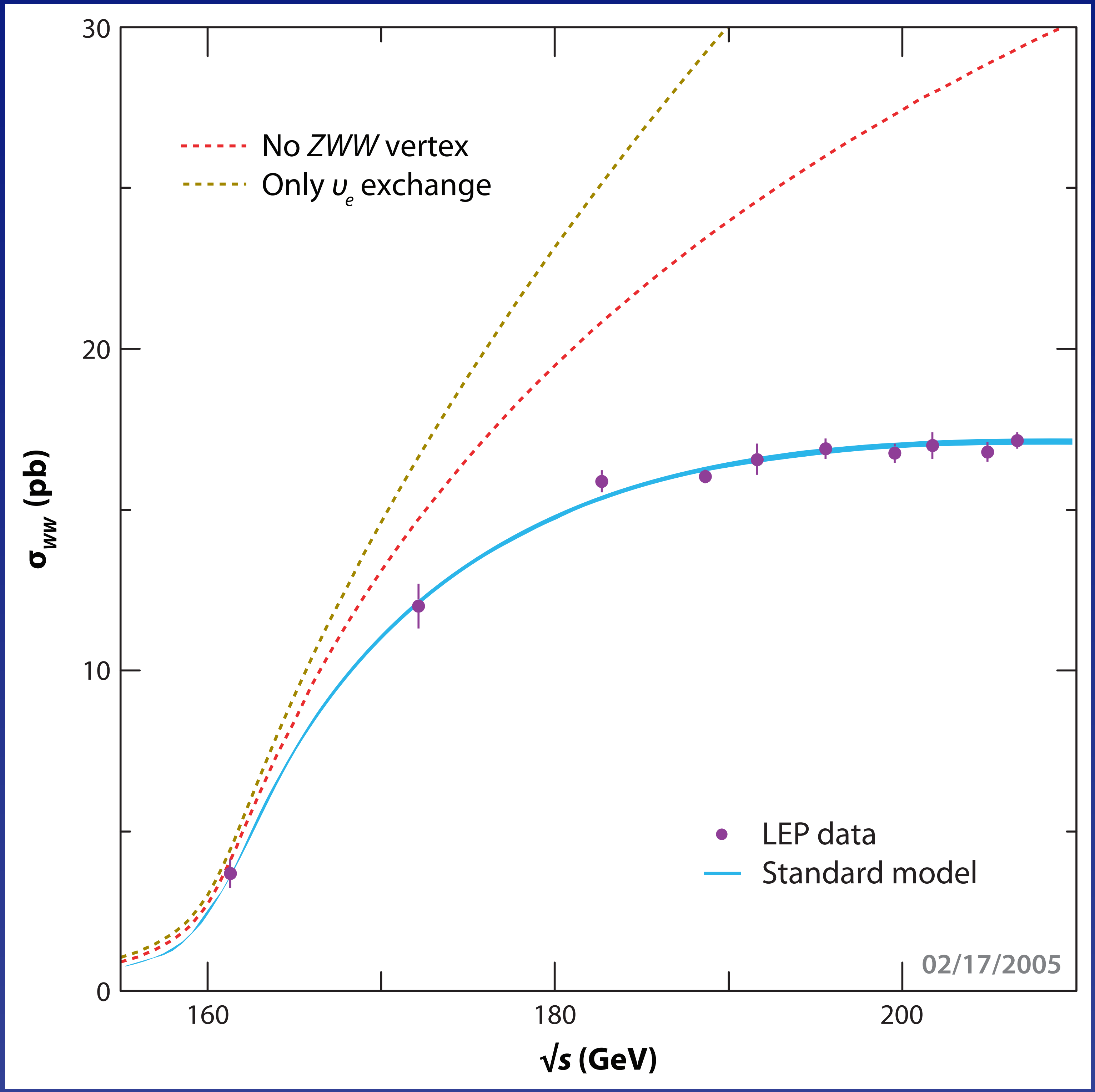
Symmetry of laws $\not\Rightarrow$ symmetry of outcomes

Studies among the Snow Crystals ... by Wilson Bentley, via NOAA Photo Library

Symmetry of laws $\not\Rightarrow$ symmetry of outcomes

Gauge symmetry (group-theory structure) tested in

$$e^+e^- \to W^+W^-$$



Reference Material

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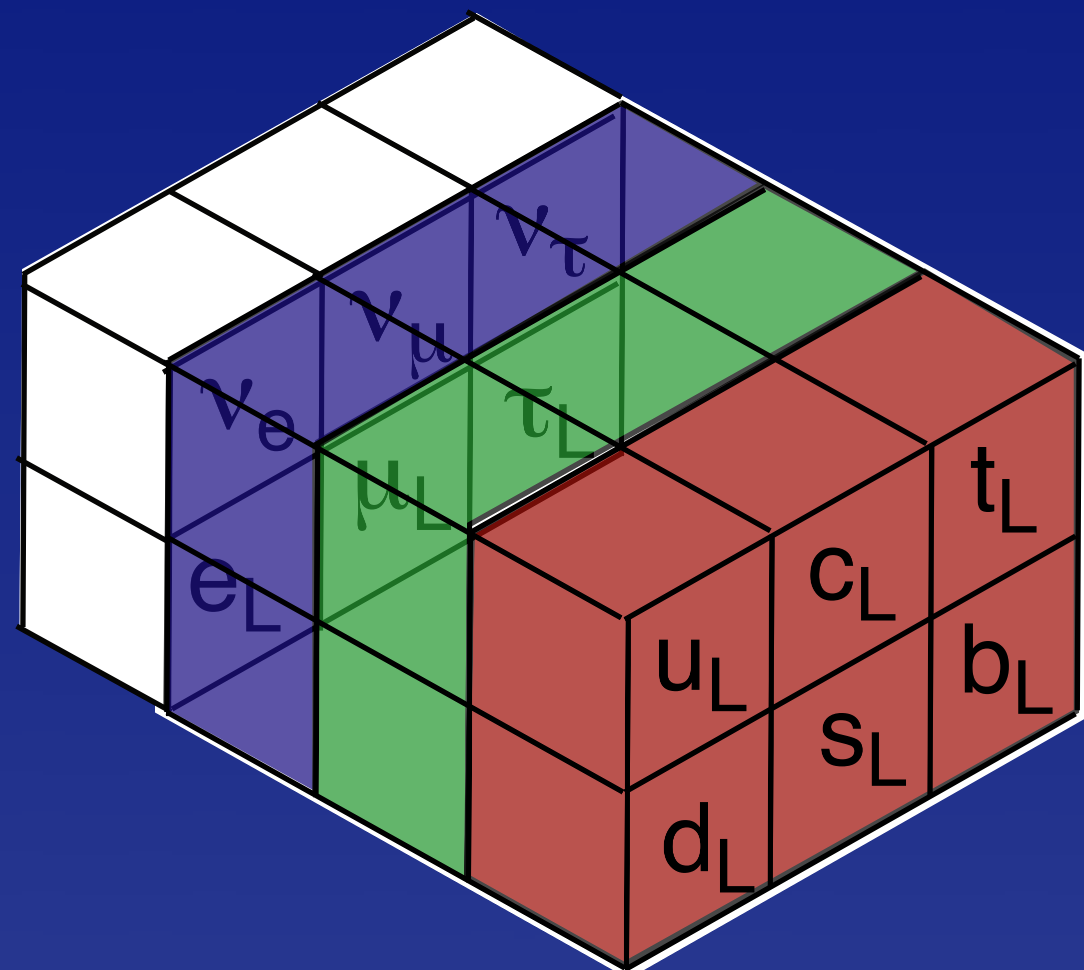
Unanswered Questions in the Electroweak Theory, *Ann. Rev. Nucl. Part. Sci.* 59, 505 (2009) [arXiv:0905.3187].

Resource Letter on Quantum Chromodynamics (with A. S. Kronfeld), *Am. J. Phys.* 78, 1081(2010) [arXiv:1002.5032].

Supercollider Physics (with E. Eichten, I. Hinchliffe, K. Lane), *Rev. Mod. Phys.* 56, 579 (1984); erratum 58, 1065 (1986).

A Unified Theory?

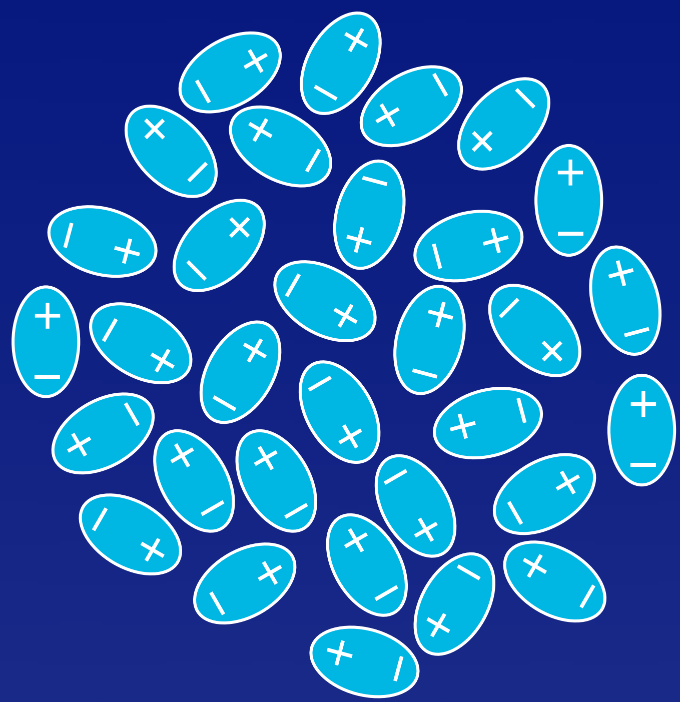
Why are atoms so remarkably neutral?

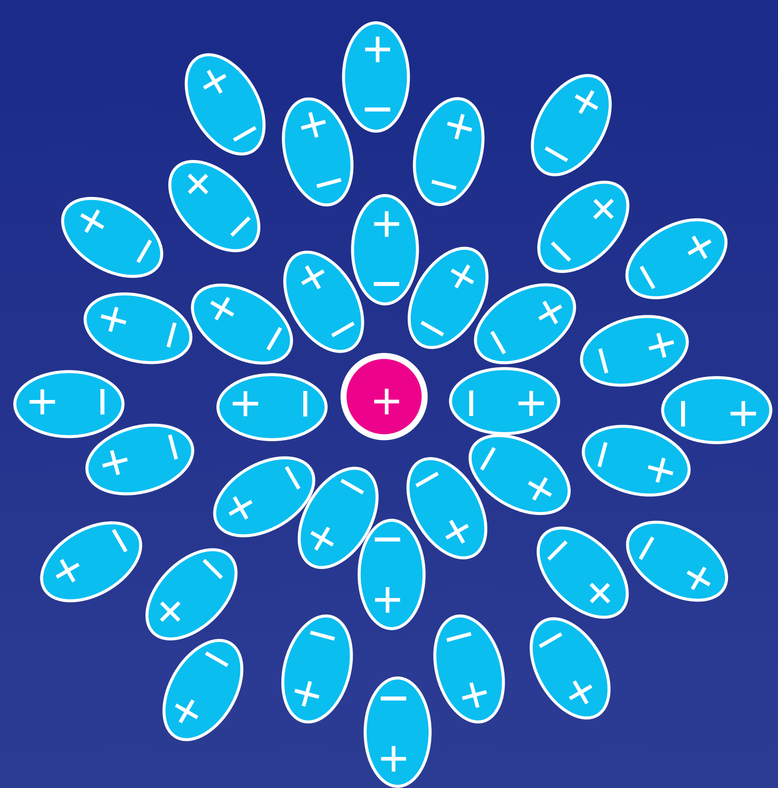


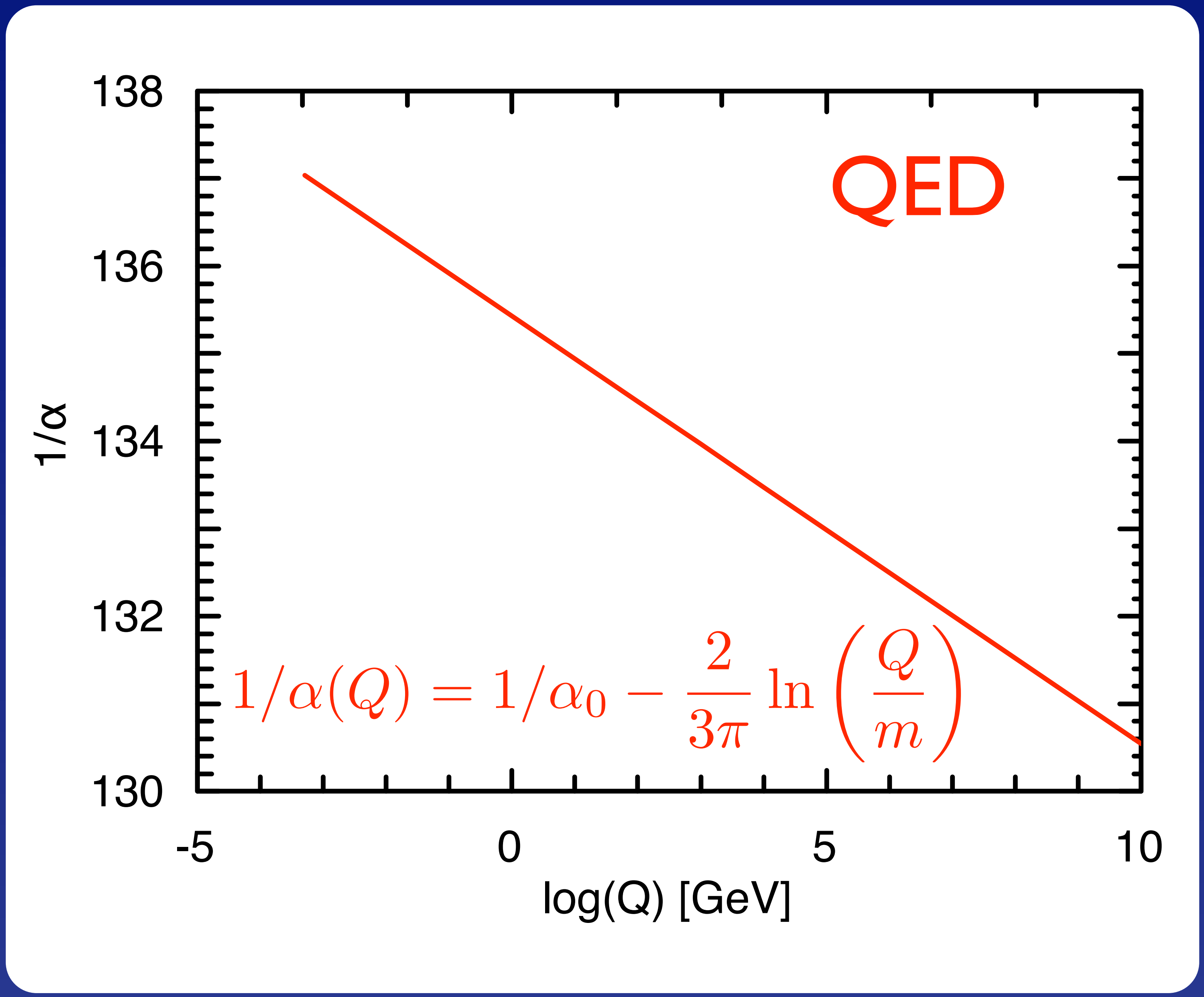
Coupling constant unification?

Extended quark–lepton families:
proton decay!

Charge screening behavior of electrodynamics

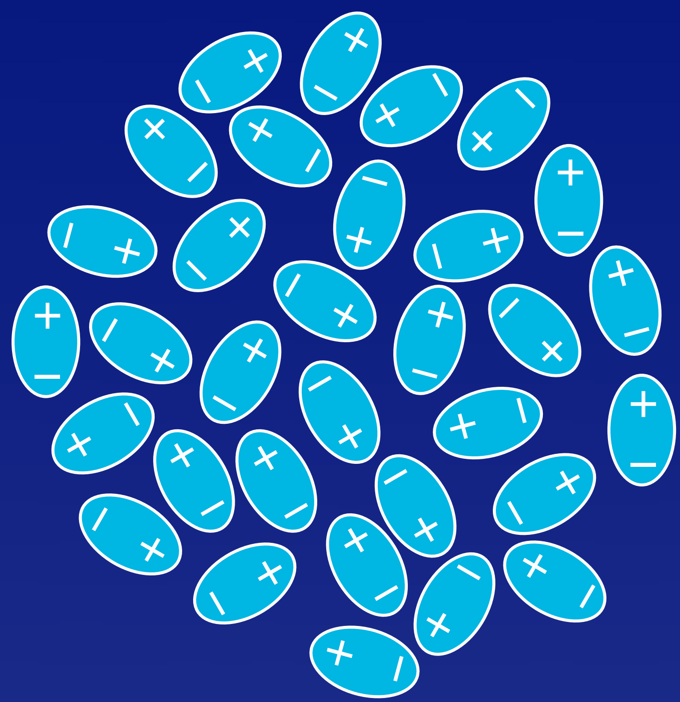


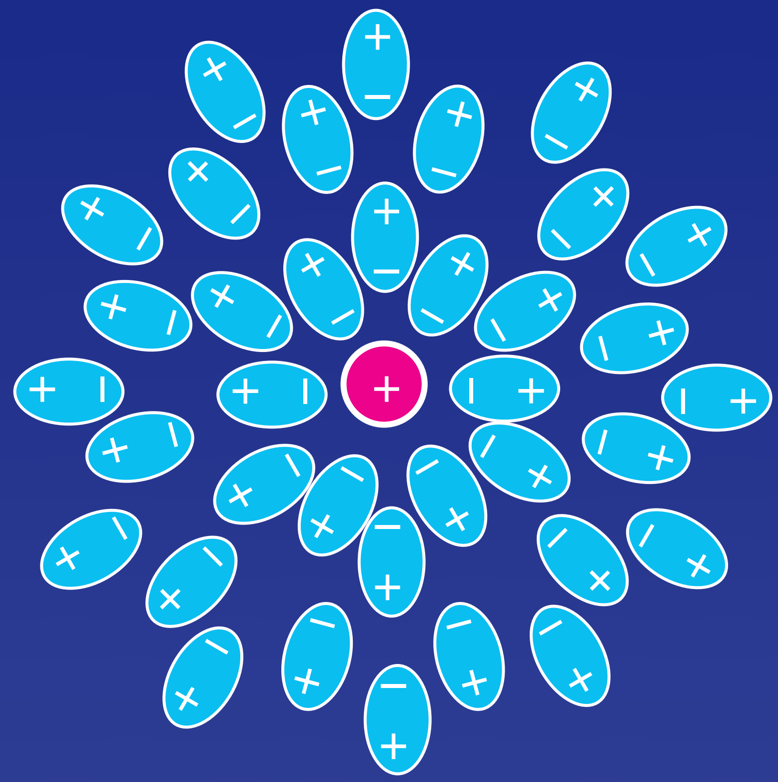


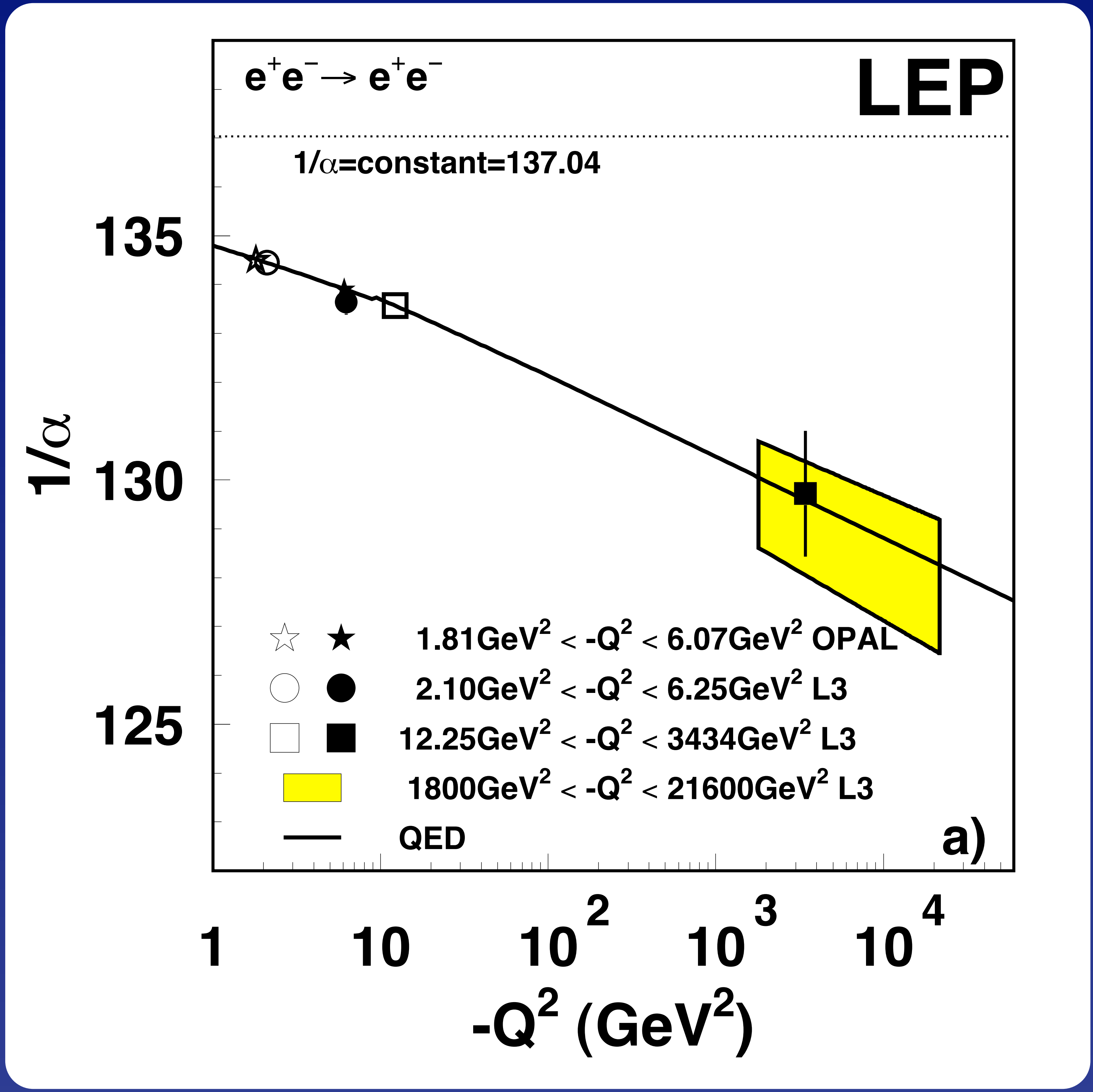


$Q_{eff} = Q/\varepsilon,\ \varepsilon > 1$

Charge screening behavior of electrodynamics





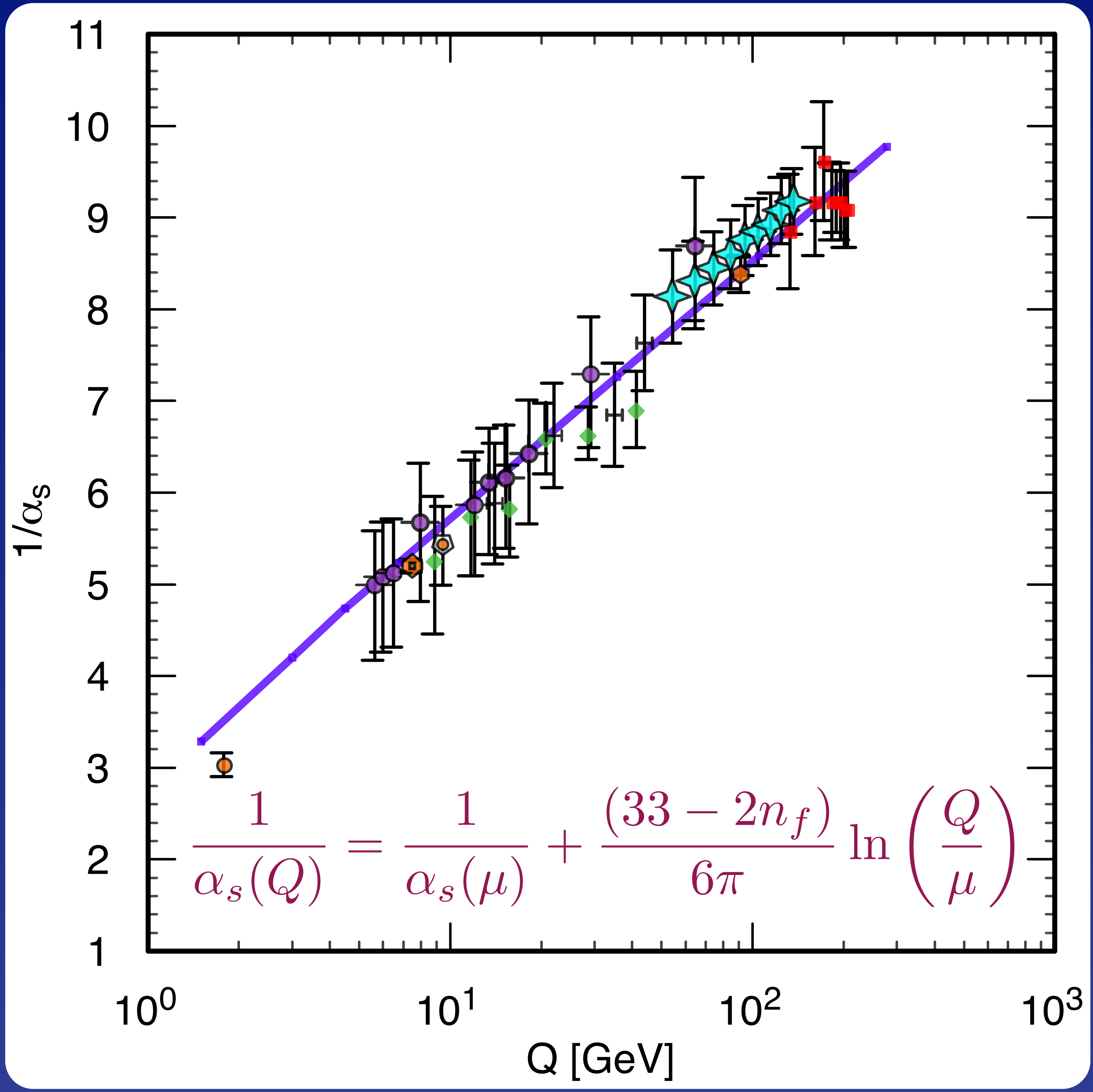


$Q_{eff} = Q/\varepsilon, \varepsilon > 1$

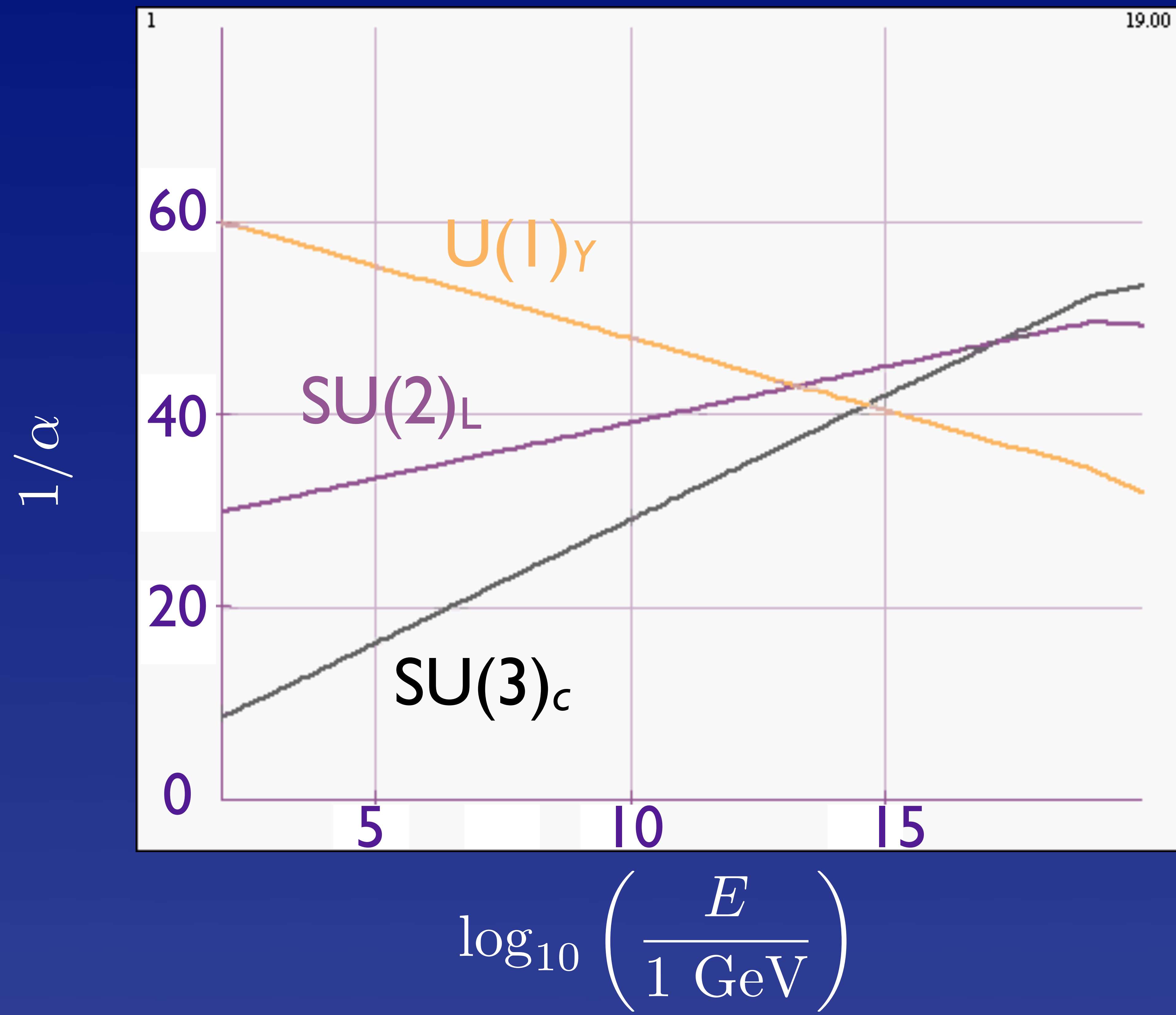
S. Mele, hep-ex/0601045

Color *antiscreening* behavior of chromodynamics

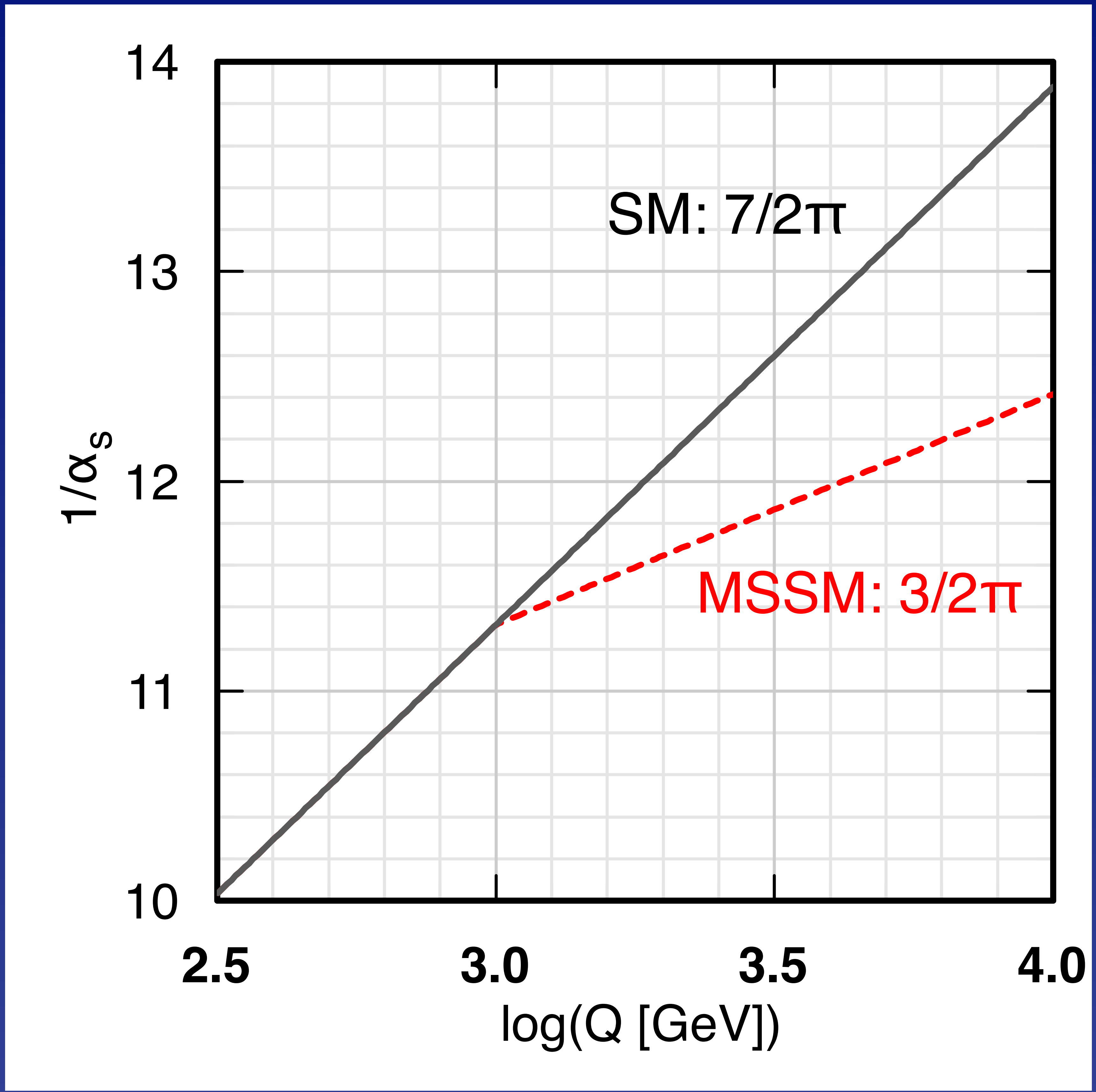
Color screening from quark pairs, camouflage from gluon cloud.



Unification of Forces?

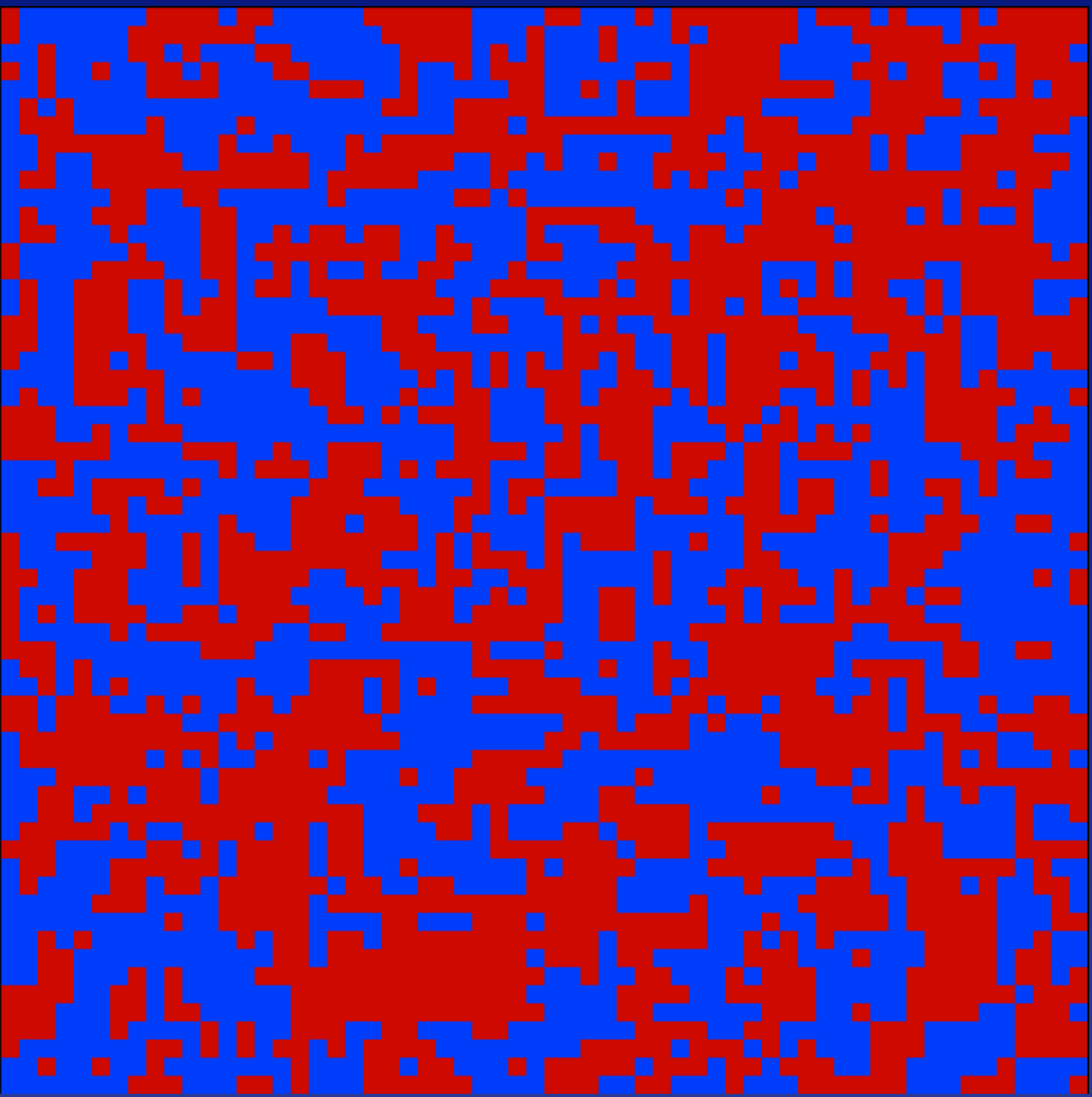


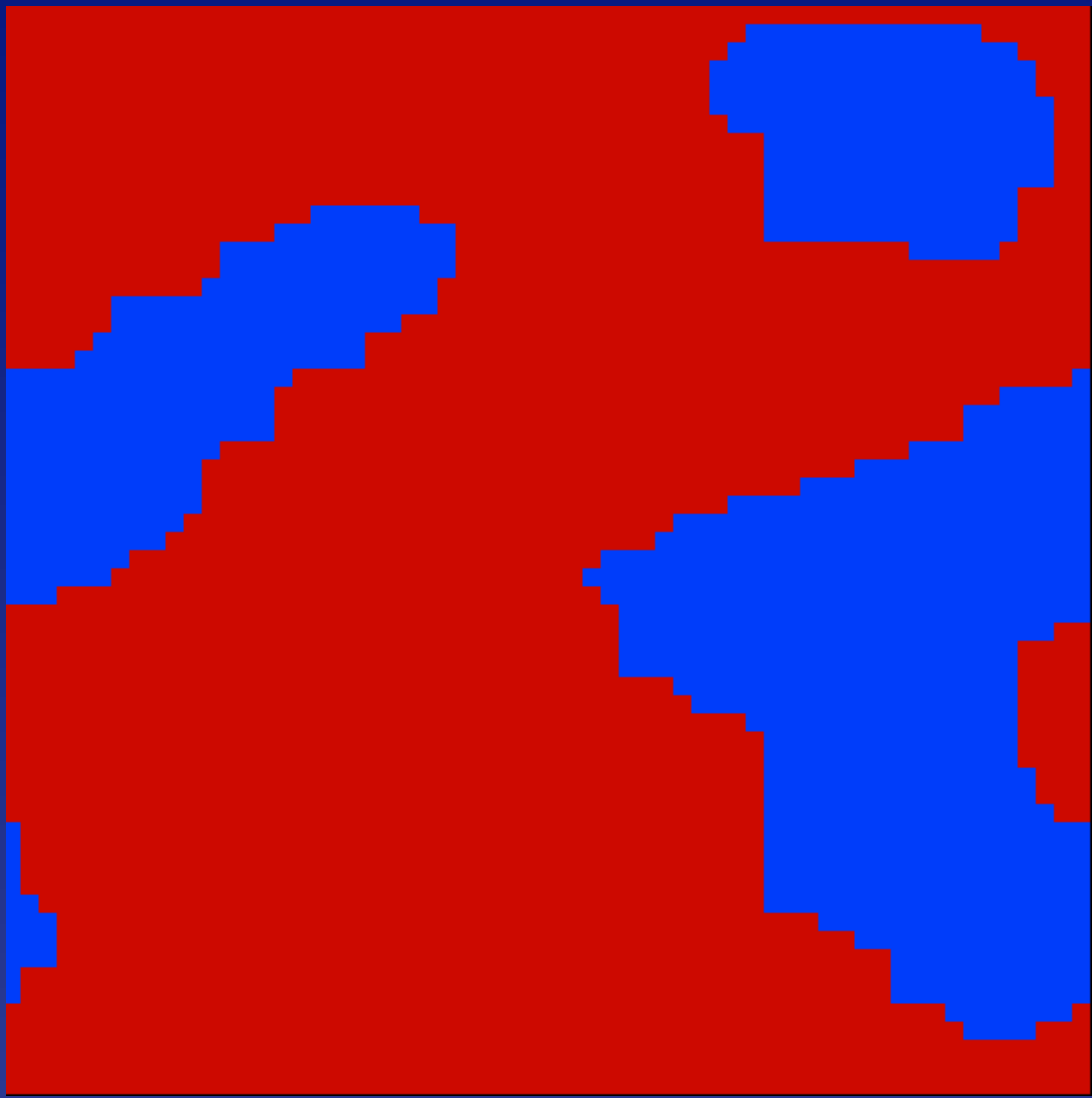
Might LHC see the change in evolution?



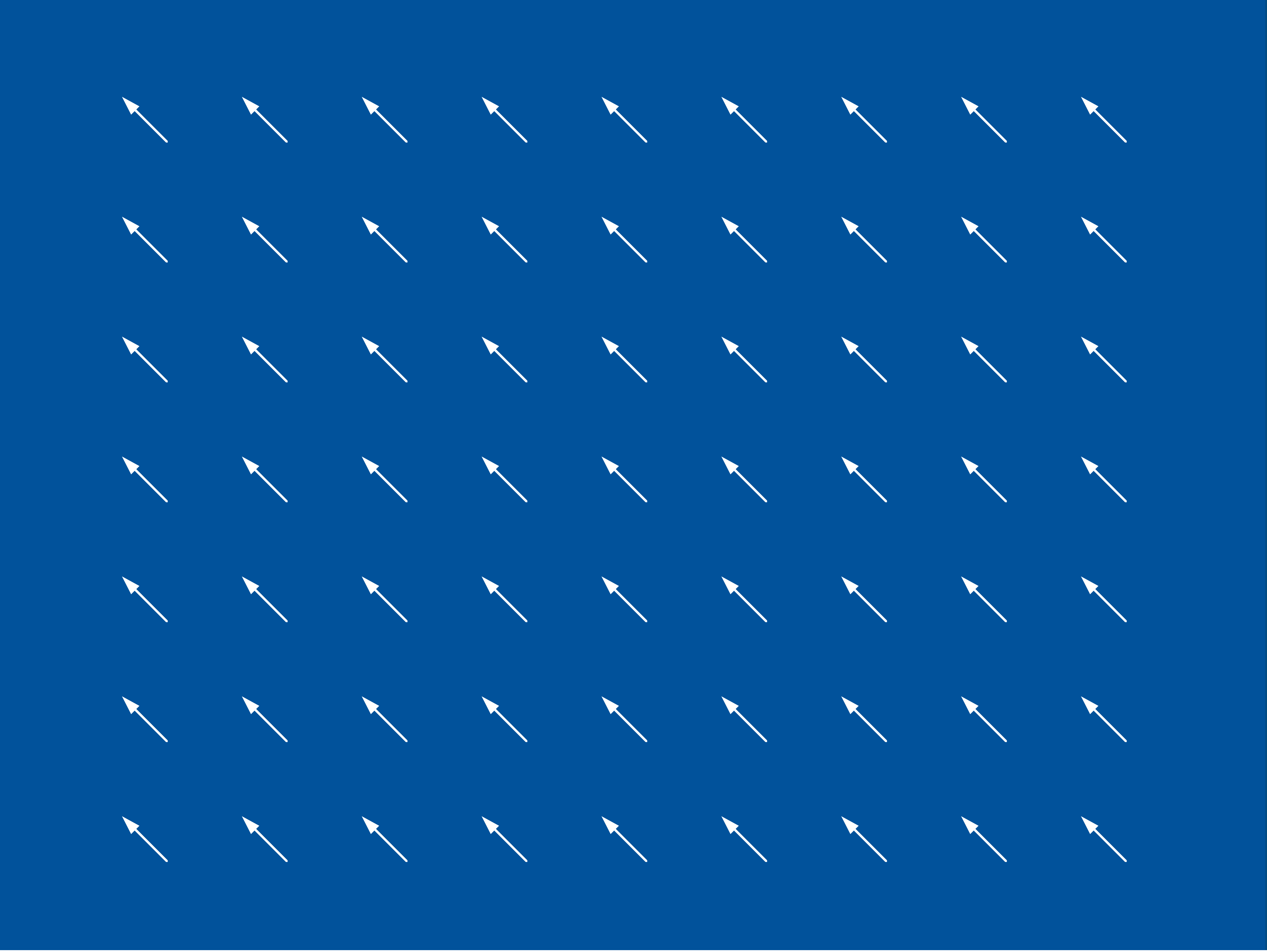
Similar change in $\sin^2\theta_W = \alpha/\alpha_2$

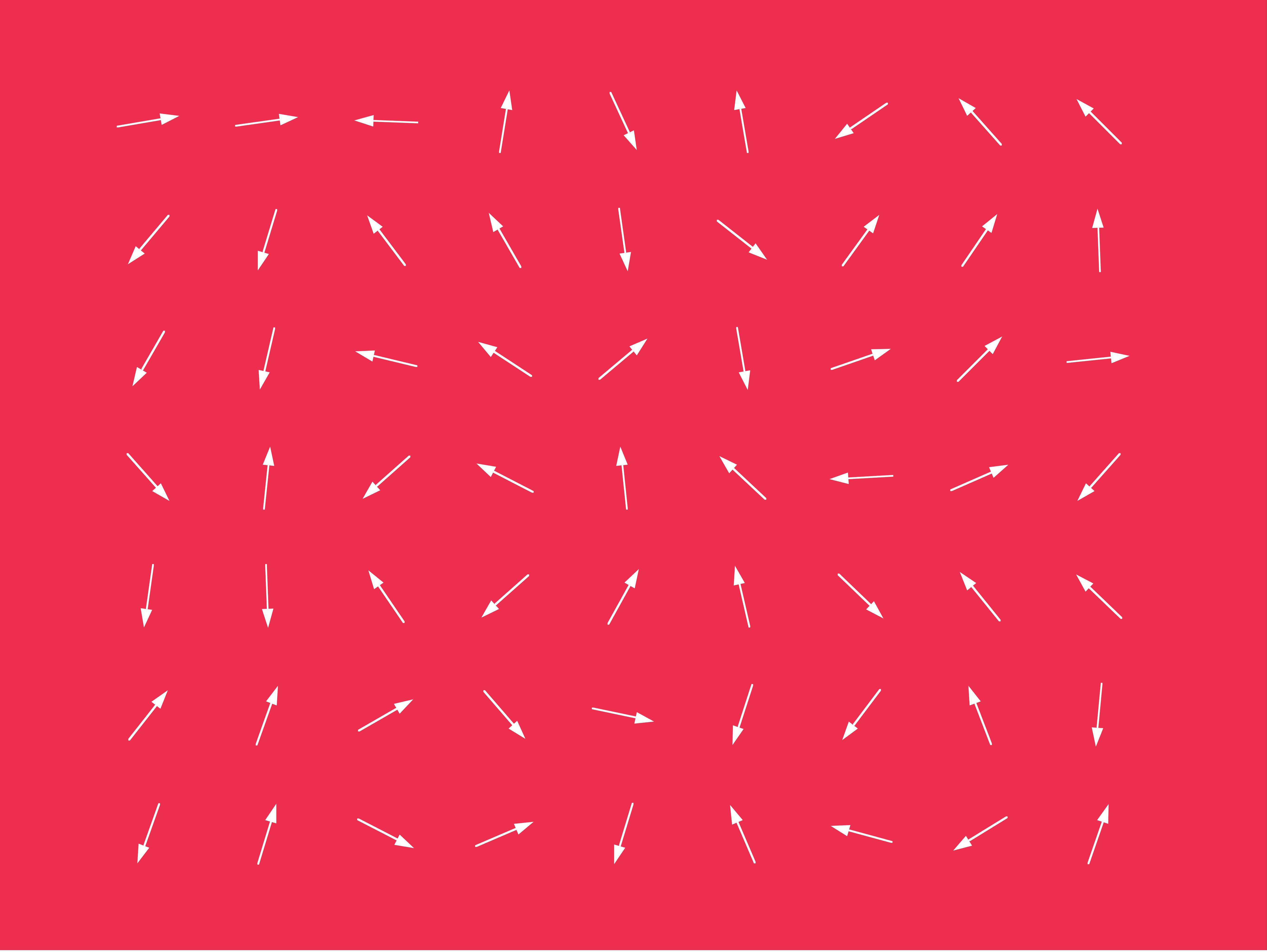
Symmetry & Disorder

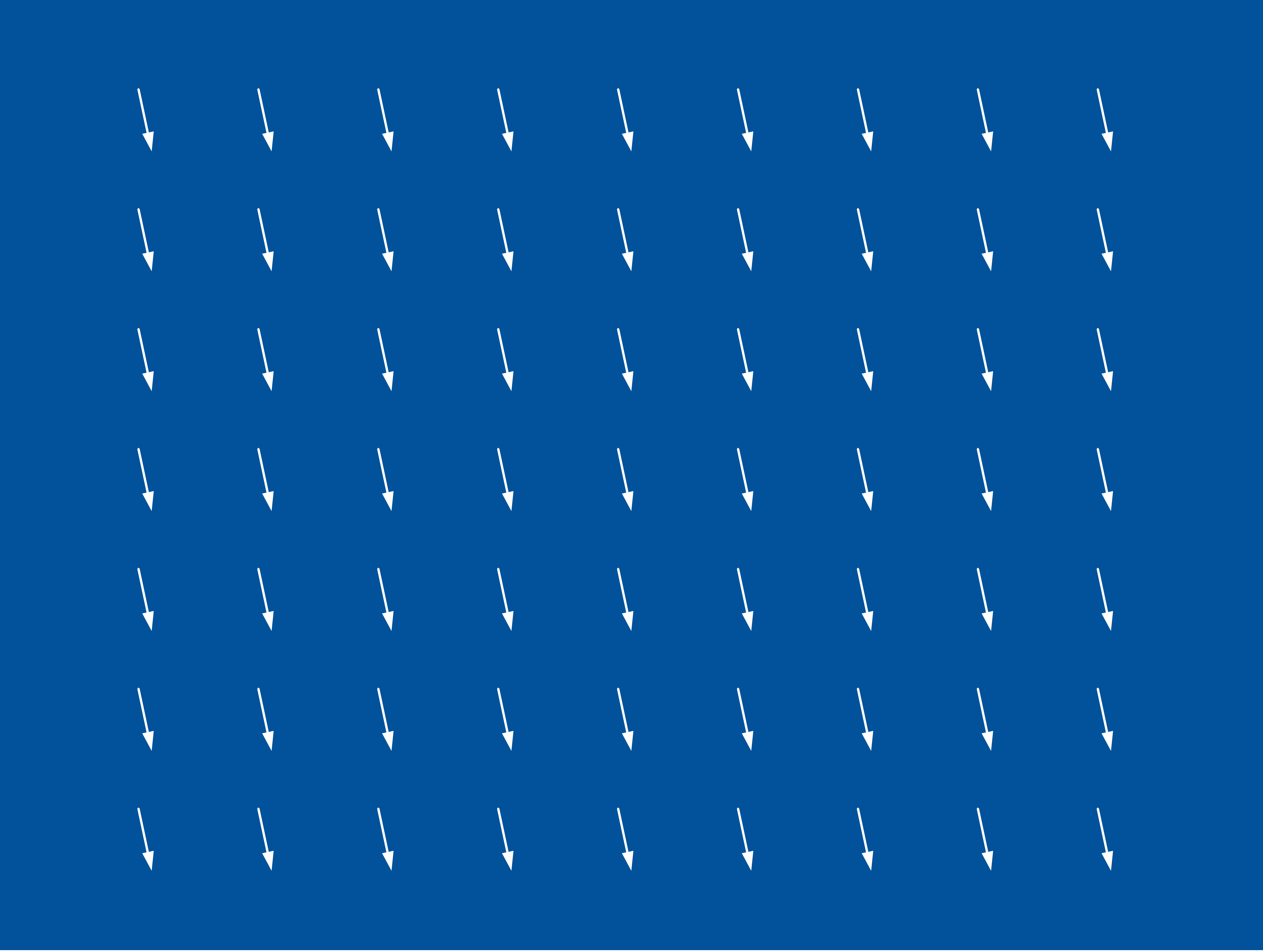




2-d Ising Model of a Ferromagnet








Meissner Effect
hidden EM symmetry
Superconductivity suggests
a field that permeates all of space
could hide electroweak symmetry

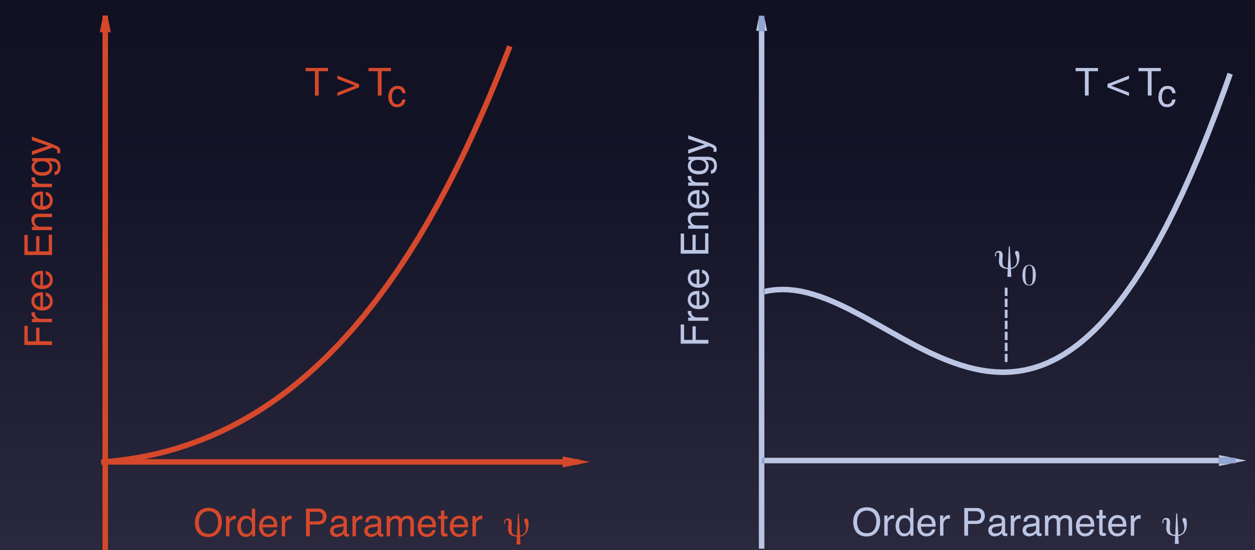
Massive Photon? *Hiding Symmetry*

Recall $\boxed{2}$ miracles of superconductivity:

- No resistance . . . . . . Meissner effect (exclusion of **B**)

Ginzburg–Landau Phenomenology (not a theory from first principles)

normal, resistive charge carriers . . . . . . + superconducting charge carriers



$$\mathbf{B} = 0: \qquad G_{\text{super}}(0) = G_{\text{normal}}(0) + \alpha\,|\psi|^2 + \beta\,|\psi|^4$$

$$T > T_c: \quad \alpha > 0 \quad \langle|\psi|^2\rangle_0 = 0$$

$$T < T_c: \quad \alpha < 0 \quad \langle|\psi|^2\rangle_0 \neq 0$$

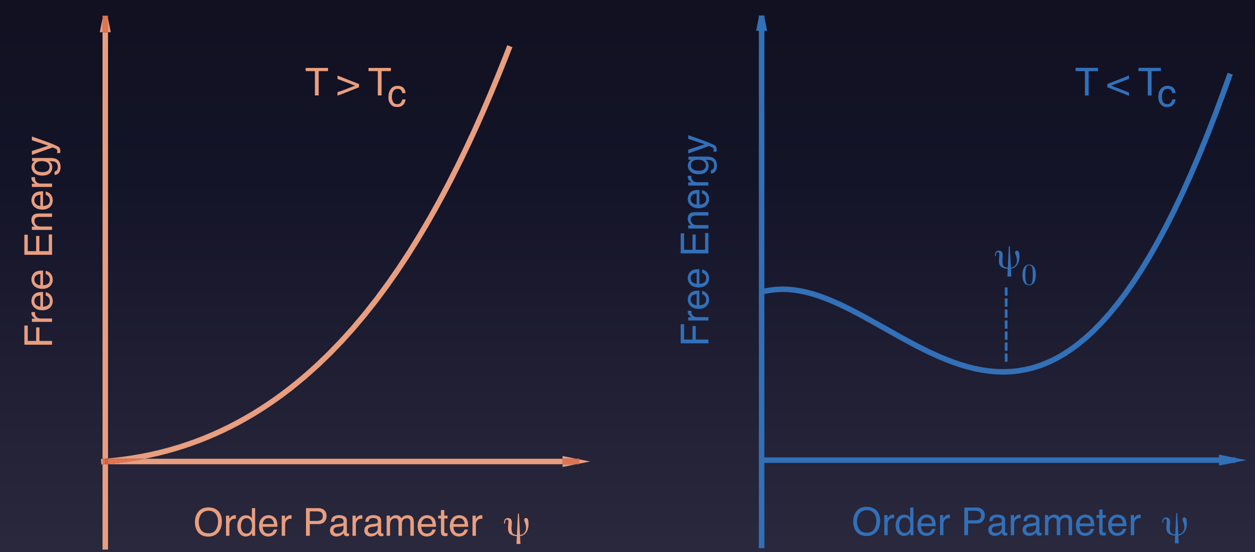
Massive Photon? *Hiding Symmetry*

Recall 2 miracles of superconductivity:

- No resistance . . .   . . . Meissner effect (exclusion of **B**)

Ginzburg–Landau Phenomenology (not a theory from first principles)

normal, resistive charge carriers . . .   . . . + superconducting charge carriers



B = 0: $$G_{\text{super}}(0) = G_{\text{normal}}(0) + \alpha\,|\psi|^2 + \beta\,|\psi|^4$$

$$T > T_c: \quad \alpha > 0 \quad \langle|\psi|^2\rangle_0 = 0$$

$$T < T_c: \quad \alpha < 0 \quad \langle|\psi|^2\rangle_0 \neq 0$$

In a nonzero magnetic field . . .

$$G_{\mathrm{super}}(\mathbf{B}) = G_{\mathrm{super}}(0) + \frac{\mathbf{B}^2}{8\pi} + \frac{1}{2m^*}\left|-i\hbar\nabla\psi - \frac{e^*}{c}\mathbf{A}\psi\right|^2$$

$$\left.\begin{array}{r} e^* = -2 \\ m^* \end{array}\right\} \text{of superconducting carriers}$$

Weak, slowly varying field: $\psi \approx \psi_0 \neq 0,\ \nabla\psi \approx 0$

Variational analysis $\rightsquigarrow$ wave equation of a *massive photon*

Photon – *gauge boson* – acquires mass

$$\boxed{\lambda^{-1} = e^\star|\langle\psi\rangle_0|/\sqrt{m^\star c^2}}$$

within superconductor

origin of Meissner effect

Spontaneous Breaking of Gauge Symmetry (1964)

Higgs

Spontaneous Breaking of Gauge Symmetry

F. Englert and R. Brout, *Phys. Rev. Lett.* 13, 321 (1964)

P. W. Higgs, *Phys. Rev. Lett.* 13, 508 (1964); *Phys. Lett.* 12, 132 (1964)

G. S. Guralnik, C. R. Hagen, T. W. B. Kibble, *Phys. Rev. Lett.* 13, 585 (1964)

Reminiscences

F. Englert, "Broken Symmetry and Yang–Mills Theory," in *50 Years of Yang–Mills Theories*, ed. G. 't Hooft, World Scientific, Singapore, 2005, p. 65 [arXiv:hep-th/0406162].

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P. W. Higgs, "SBGT and all that," in *Discovery of weak neutral currents: the weak interaction before and after, Edited by A. K. Mann and D. B. Cline, AIP Conf. Proc*. 300, *159 (1994); "My life as a boson: The story of 'The Higgs'," Int. J. Mod. Phys. A* 17S1, 86 (2002).

T. W. B. Kibble "Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism (history)," Scholarpedia 4(1), 8741 (2009); http://www.scholarpedia.org/article/Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism (history).

Hiding EW Symmetry

Higgs mechanism: relativistic generalization of Ginzburg-Landau superconducting phase transition

- Introduce a complex doublet of scalar fields

$$\phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad Y_\phi = +1$$

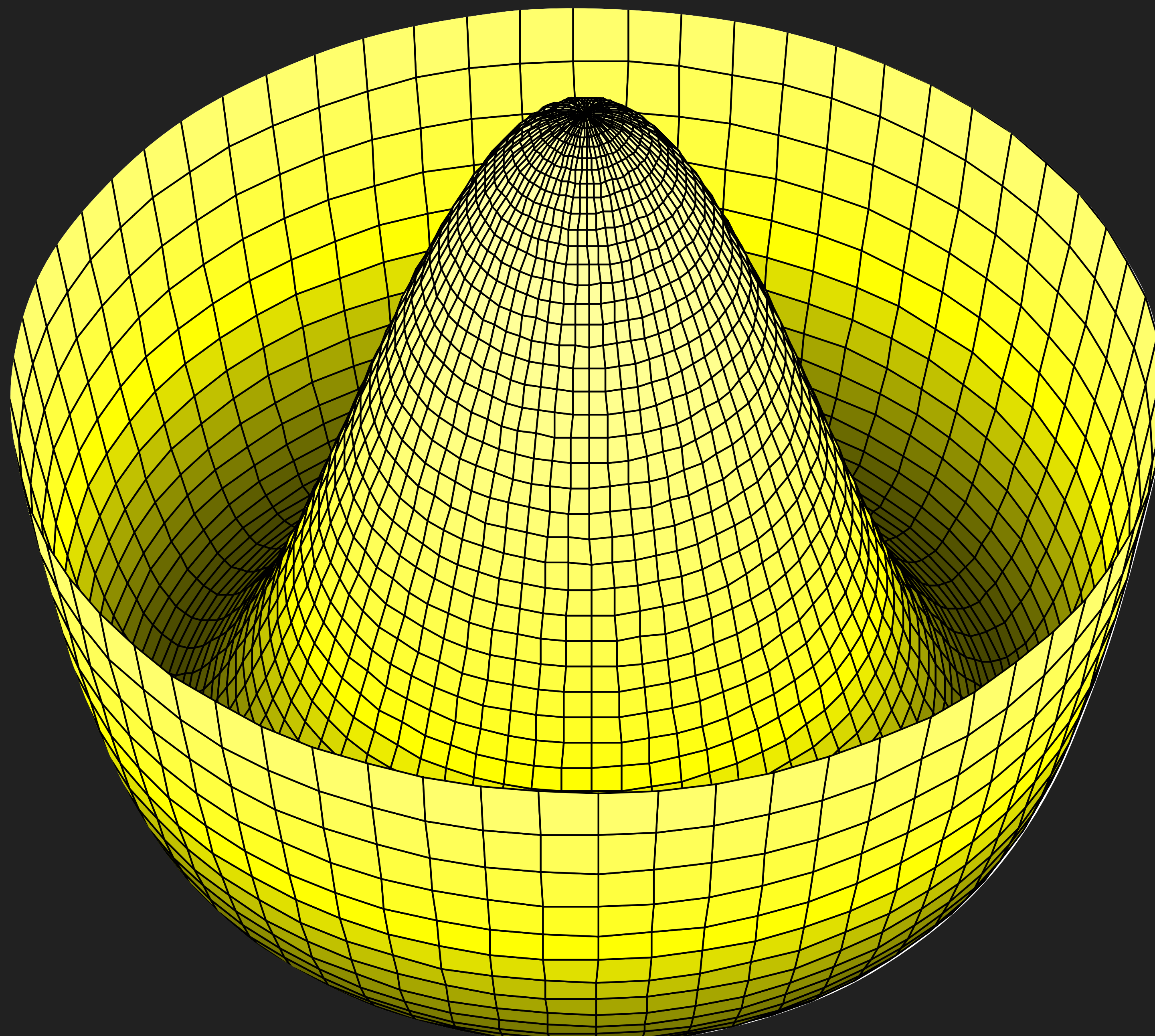
- Add to $\mathcal{L}$ (gauge-invariant) terms for interaction and propagation of the scalars,

$$\mathcal{L}_{\text{scalar}} = (\mathcal{D}^\mu \phi)^\dagger (\mathcal{D}_\mu \phi) - V(\phi^\dagger \phi),$$

  where $\mathcal{D}_\mu = \partial_\mu + i\frac{g'}{2}\mathcal{A}_\mu Y + i\frac{g}{2}\vec{\tau} \cdot \vec{b}_\mu$ and

$$\boxed{V(\phi^\dagger \phi) = \mu^2(\phi^\dagger \phi) + |\lambda| (\phi^\dagger \phi)^2}$$

- Add a Yukawa interaction $\mathcal{L}_{\text{Yukawa}} = -\zeta_e \left[\overline{\mathrm{R}}(\phi^\dagger \mathrm{L}) + (\overline{\mathrm{L}}\phi)\mathrm{R}\right]$



“Fifth Force” determines potential

- Arrange self-interactions so vacuum corresponds to a broken-symmetry solution: $\mu^2 < 0$

  Choose minimum energy (vacuum) state for vacuum expectation value

$$\langle\phi\rangle_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}, \quad v = \sqrt{-\mu^2/|\lambda|}$$

  Hides (breaks) $SU(2)_L$ and $U(1)_Y$

  but preserves $U(1)_{\mathrm{em}}$ invariance

  Invariance under $\mathcal{G}$ means $e^{i\alpha\mathcal{G}}\langle\phi\rangle_0 = \langle\phi\rangle_0$, so $\mathcal{G}\langle\phi\rangle_0 = 0$

$$\tau_1\langle\phi\rangle_0 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix} \neq 0 \quad \text{broken!}$$

$$\tau_2\langle\phi\rangle_0 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} -iv/\sqrt{2} \\ 0 \end{pmatrix} \neq 0 \quad \text{broken!}$$

$$\tau_3\langle\phi\rangle_0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} 0 \\ -v/\sqrt{2} \end{pmatrix} \neq 0 \quad \text{broken!}$$

$$Y\langle\phi\rangle_0 = Y_\phi\langle\phi\rangle_0 = +1\langle\phi\rangle_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \neq 0 \quad \text{broken!}$$

Examine electric charge operator Q on the (neutral) vacuum

$$\begin{aligned} Q\langle\phi\rangle_0 &= \tfrac{1}{2}(\tau_3 + Y)\langle\phi\rangle_0 \\ &= \tfrac{1}{2}\begin{pmatrix} Y_\phi + 1 & 0 \\ 0 & Y_\phi - 1 \end{pmatrix}\langle\phi\rangle_0 \\ &= \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \\ &= \begin{pmatrix} 0 \\ 0 \end{pmatrix} \qquad \textit{unbroken!} \end{aligned}$$

Four original generators are broken, *electric charge is not*

- $\mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{U}(1)_Y \rightarrow\ U(1)_\mathrm{em}$ (will verify)
- Expect massless photon
- Expect gauge bosons corresponding to

$$\tau_1,\ \tau_2,\ \tfrac{1}{2}(\tau_3 - Y) \equiv K \quad \text{to acquire masses}$$

Expand about the vacuum state

Let $\phi = \begin{pmatrix} 0 \\ (v+\eta)/\sqrt{2} \end{pmatrix}$; in *unitary gauge*

$$\begin{aligned} \mathcal{L}_{\text{scalar}} &= \tfrac{1}{2}(\partial^\mu \eta)(\partial_\mu \eta) - \mu^2\eta^2 \\ &+ \frac{v^2}{8}[g^2 \left|b^1_\mu - ib^2_\mu\right|^2 + (g'\mathcal{A}_\mu - gb^3_\mu)^2] \\ &+ \text{interaction terms} \end{aligned}$$

"Higgs boson" η has acquired $(\text{mass})^2$ $M_H^2 = -2\mu^2 > 0$

$$\text{Define } W^\pm_\mu = \frac{b^1_\mu \mp ib^2_\mu}{\sqrt{2}}$$

$$\frac{g^2v^2}{8}(\left|W^+_\mu\right|^2 + \left|W^-_\mu\right|^2) \Longleftrightarrow M_{W^\pm} = gv/2$$

$(v^2/8)(g'\mathcal{A}_\mu - g b^3_\mu)^2 \ldots$

Now define orthogonal combinations

$$Z_\mu = \frac{-g'\mathcal{A}_\mu + g b^3_\mu}{\sqrt{g^2 + g'^2}} \qquad A_\mu = \frac{g\mathcal{A}_\mu + g' b^3_\mu}{\sqrt{g^2 + g'^2}}$$

$$M_{Z^0} = \sqrt{g^2 + g'^2}\, v/2 = M_W \sqrt{1 + g'^2/g^2}$$

$\boxed{A_\mu \text{ remains massless}}$

$$
\begin{aligned}
\mathcal{L}_{\text{Yukawa}} &= -\zeta_e \frac{(v+\eta)}{\sqrt{2}} (\bar{e}_{\mathsf{R}} e_{\mathsf{L}} + \bar{e}_{\mathsf{L}} e_{\mathsf{R}}) \\
&= -\frac{\zeta_e v}{\sqrt{2}} \bar{e} e - \frac{\zeta_e \eta}{\sqrt{2}} \bar{e} e
\end{aligned}
$$

electron acquires $m_e = \zeta_e v/\sqrt{2}$

Higgs-boson coupling to electrons: m_e/v $\quad$ ($\propto$ mass)

Desired particle content . . . plus a Higgs scalar

Values of couplings, electroweak scale v?

Then analyze interactions . . .

The importance of the 1-TeV scale

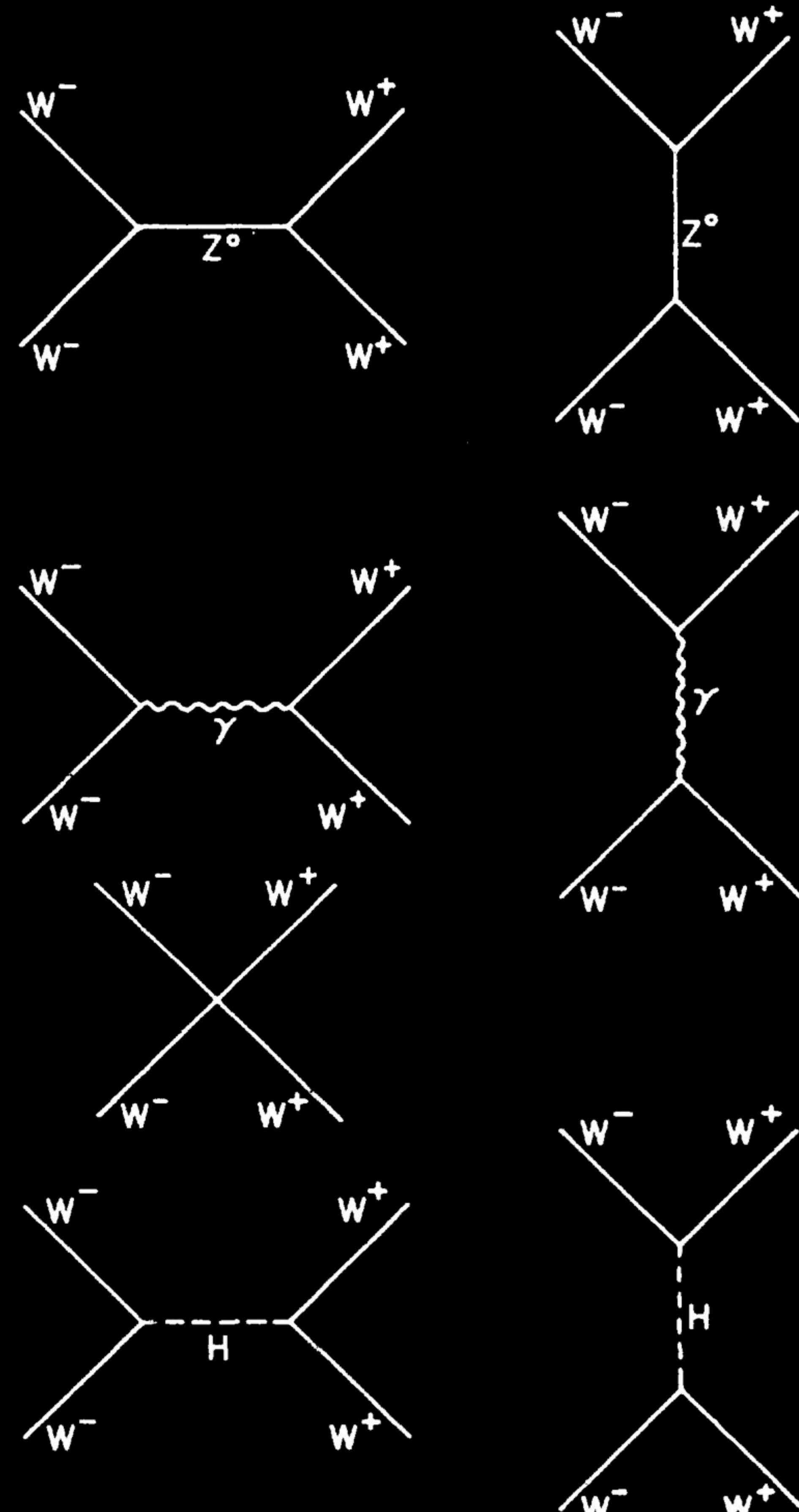
EW theory does not predict Higgs-boson mass,

but partial-wave unitarity defines tipping point

Gedanken experiment: high-energy scattering of

$$W_L^+ W_L^- \quad Z_L^0 Z_L^0/\sqrt{2} \quad HH/\sqrt{2} \quad HZ_L^0$$

L: longitudinal, $1/\sqrt{2}$ for identical particles


W^-
W^+
Z^0
W^-
W^+
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W^+

The importance of the 1-TeV scale . . .

In HE limit, s-wave amplitudes $\propto G_F M_H^2$

$$\lim_{s \gg M_H^2} (a_0) \to \frac{-G_F M_H^2}{4\pi\sqrt{2}} \cdot \begin{bmatrix} 1 & 1/\sqrt{8} & 1/\sqrt{8} & 0 \\ 1/\sqrt{8} & 3/4 & 1/4 & 0 \\ 1/\sqrt{8} & 1/4 & 3/4 & 0 \\ 0 & 0 & 0 & 1/2 \end{bmatrix}$$

Require that largest eigenvalue respect partial-wave unitarity condition $|a_0| \leq 1$

$$\Longrightarrow \quad M_H \leq \left(\frac{8\pi\sqrt{2}}{3G_F} \right)^{1/2} = 1 \text{ TeV}$$

condition for perturbative unitarity

The importance of the 1-TeV scale . . .

If the bound is respected

- weak interactions remain weak at all energies
- perturbation theory is everywhere reliable

If the bound is violated

- perturbation theory breaks down
- weak interactions among $W^{\pm}$, Z, H become strong on 1-TeV scale

New phenomena are to be found in the EW interactions at energies not much larger than 1 TeV

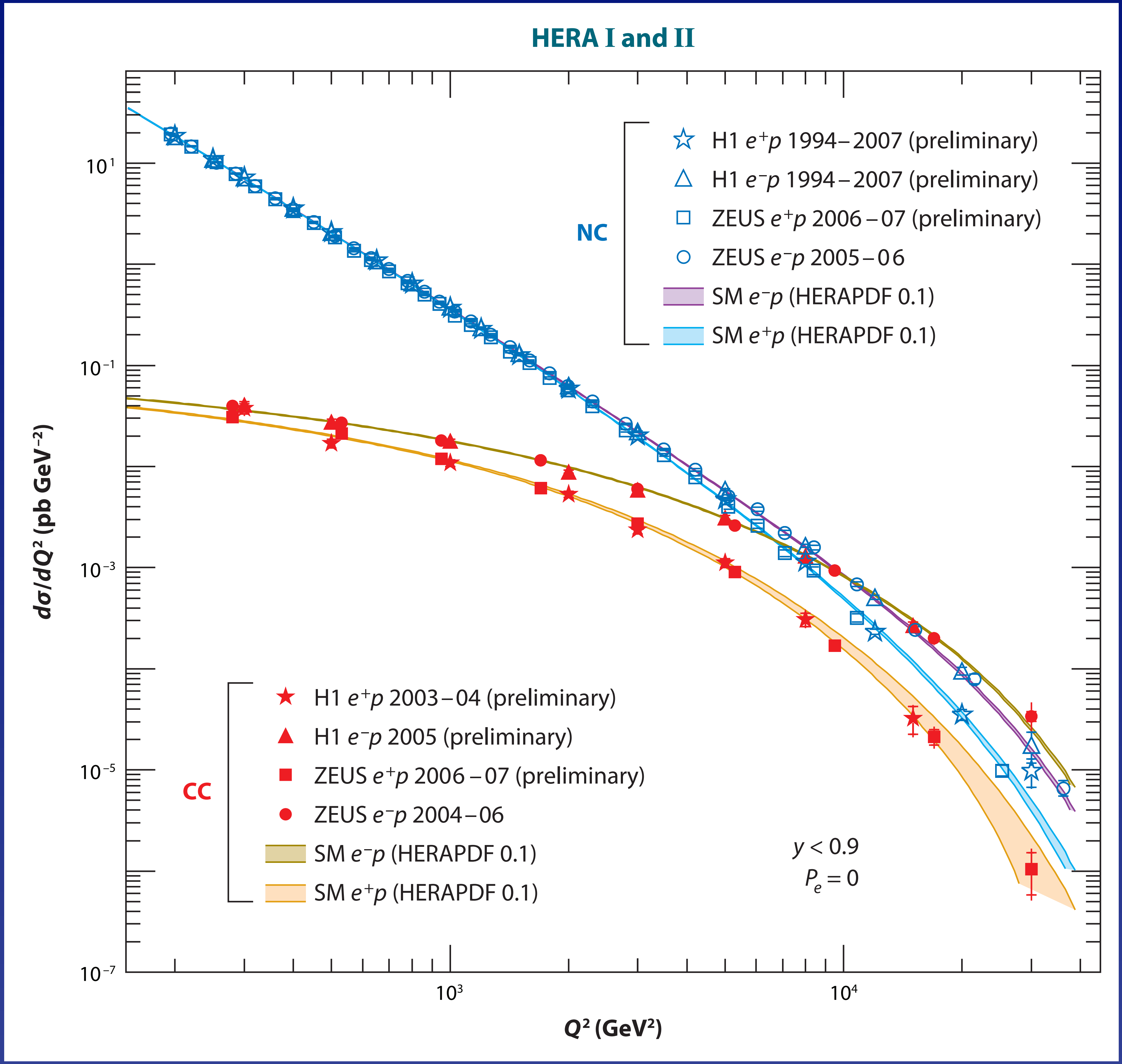
“Standard” Electroweak Theory

Higgs boson: massive particle with spin zero
hides electroweak symmetry
gives mass to *W* and *Z*
gives mass to electron, quarks, etc.

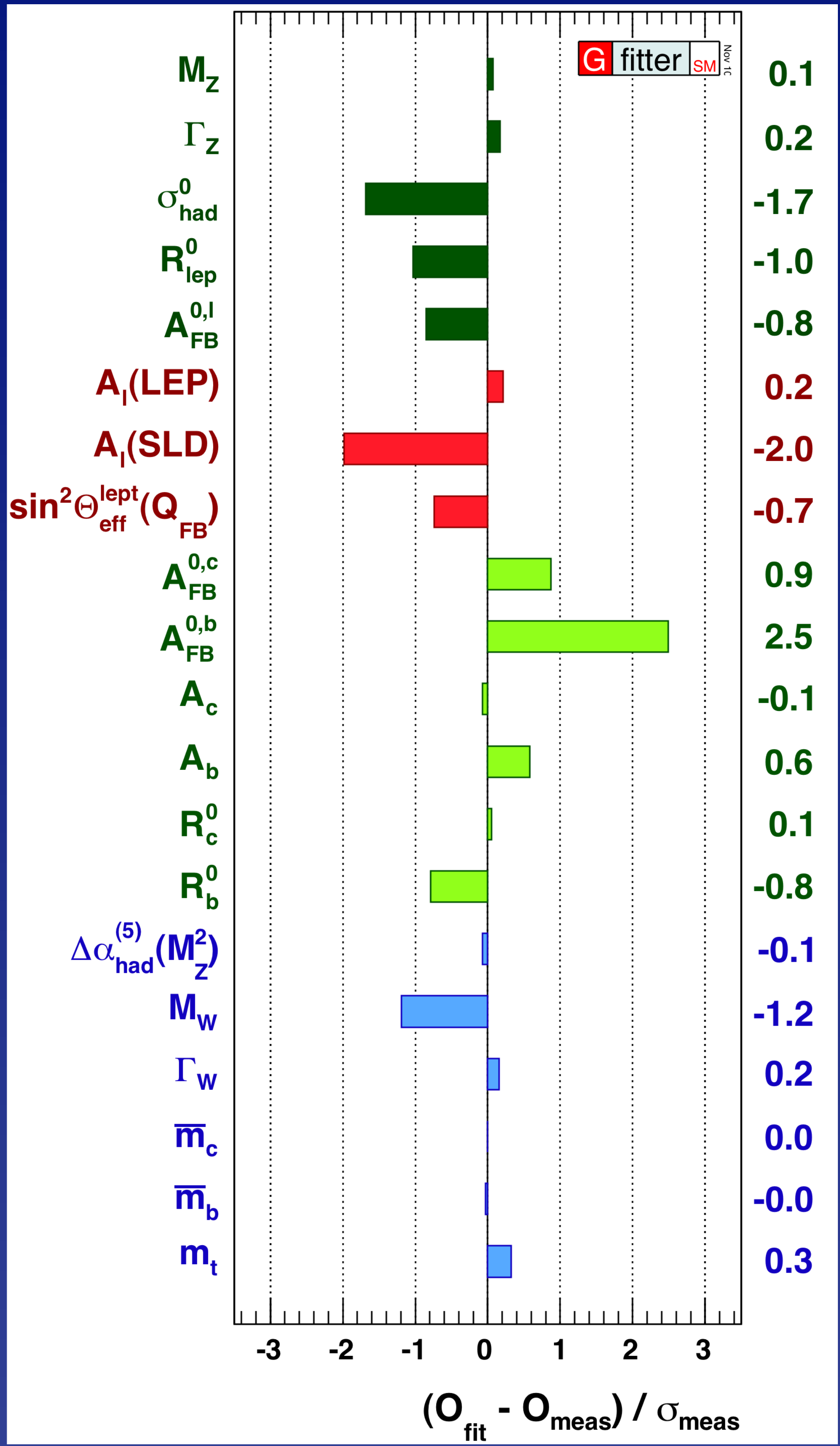
Theory does not predict Higgs-boson mass

Not yet observed!

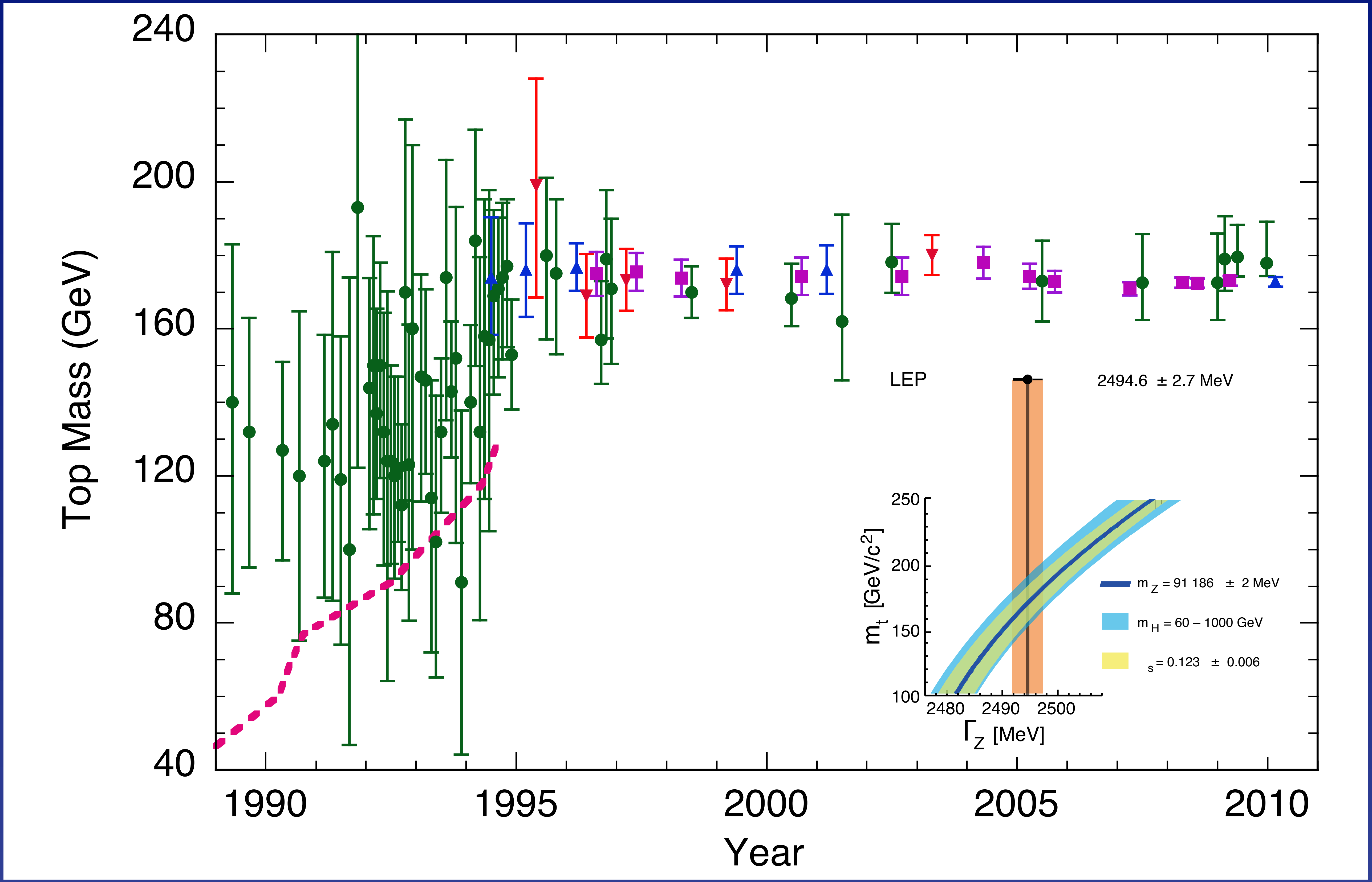
Similar strengths of weak & EM couplings



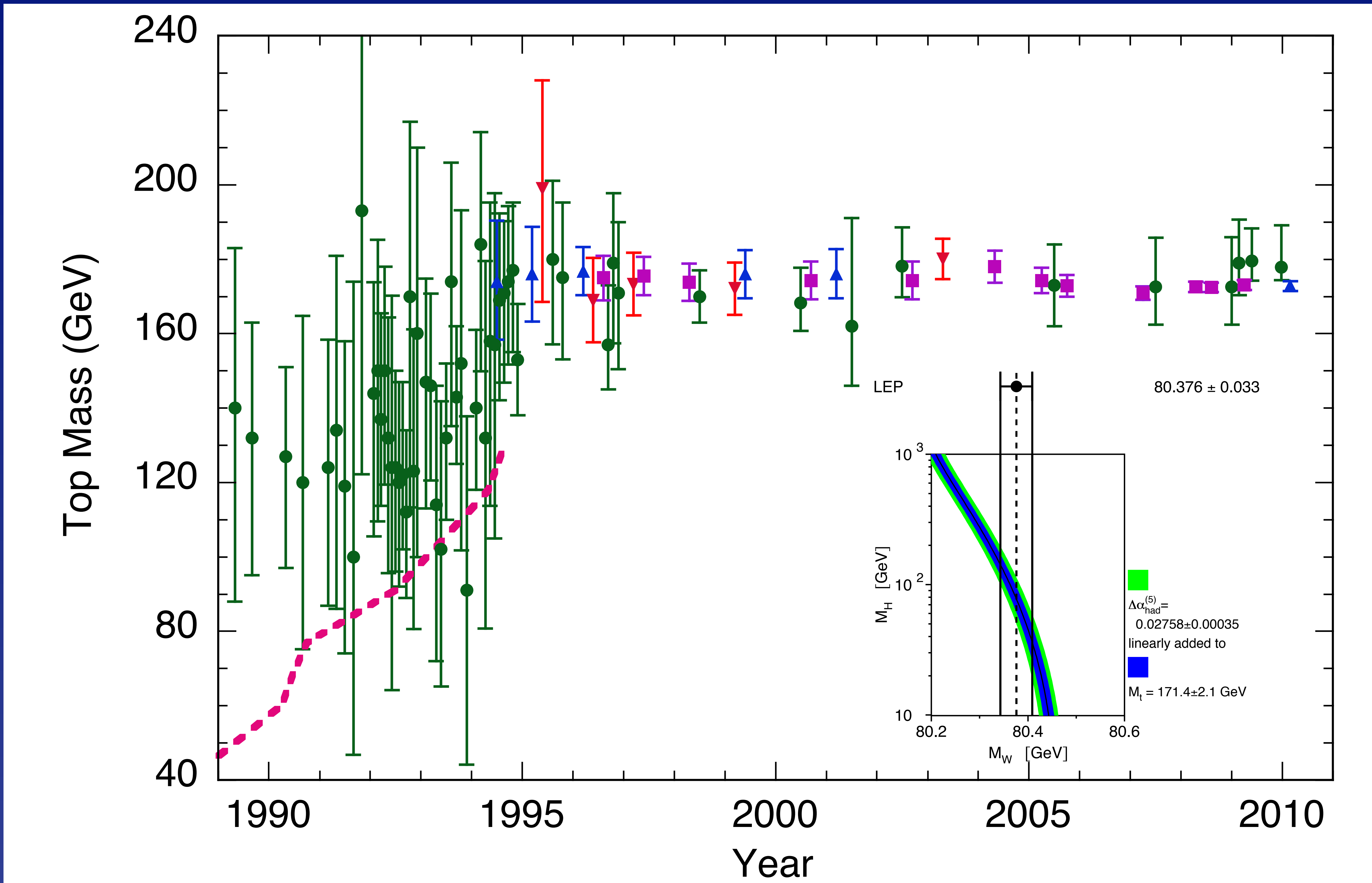
Electroweak Theory Survives Many Tests



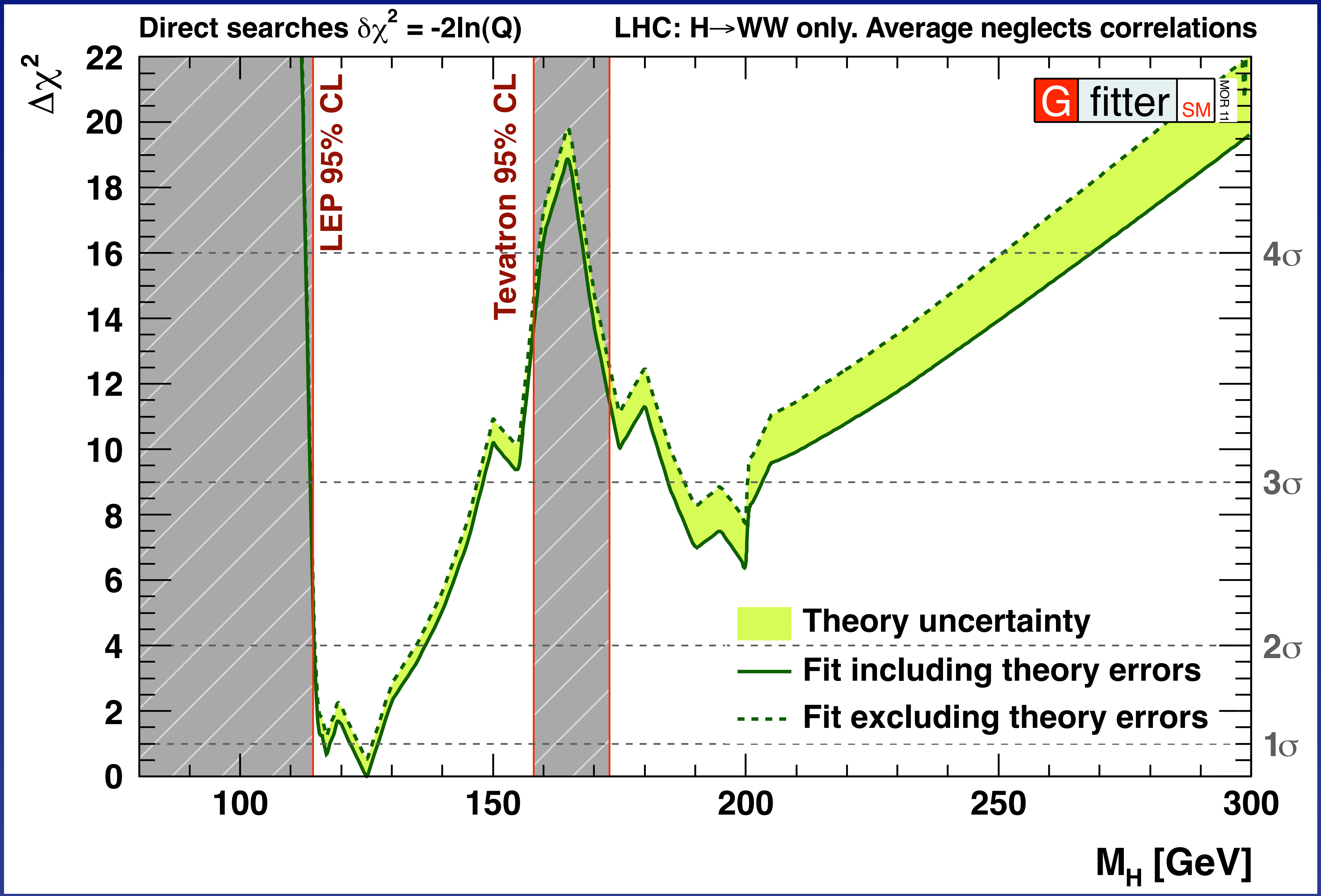
Electroweak Theory Anticipates Discoveries



Electroweak Theory Anticipates Discoveries



Where the SM Higgs Boson Is Not



BSM: Heavy Higgs allowed, even natural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Man kann Maxwells wunderbare elektromagnetische Lichttheorie nicht studieren, ohne bisweilen die Empfindung zu haben, als wohne den mathematischen Formeln selbständiges Leben und eigener Verstand inne, als seien dieselben klüger als wir, klüger sogar als ihr Erfinder, als gäben sie uns mehr heraus, als seinerzeit in sie hineingelegt wurde.

One cannot study Maxwell's marvelous electromagnetic theory of light without sometimes having the feeling that these mathematical formulae have an independent existence and an intelligence of their own, that they are wiser than we are, wiser even than their discoverers, that we got more of them than was originally put into them.

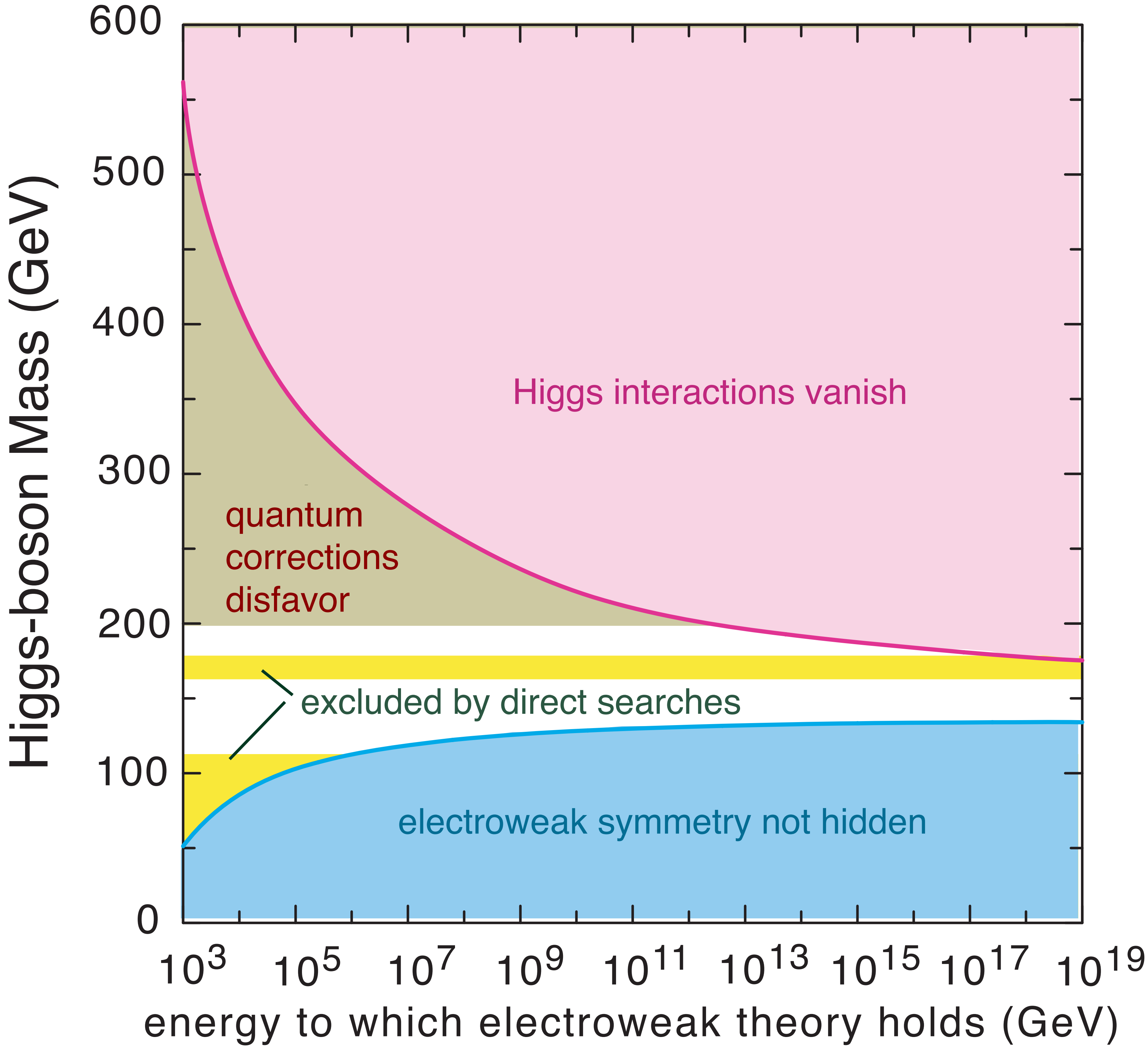
Heinrich Hertz, "Über die Beziehungen zwischen Licht und Elektrizität," *Gesammelte Werke* I S. 339-354: S. 344.

EW theory holds from 10^{-18} m to 10^{8} m

It is unlikely to be complete

Limits of Validity of the Electroweak Theory

Consistent to M_{Planck} if 134 GeV $\lesssim M_H \lesssim$ 177 GeV



An unknown agent hides electroweak symmetry

✳ A force of a new character, based on interactions of an elementary scalar

✳ A new gauge force, perhaps acting on undiscovered constituents

✳ A residual force that emerges from strong dynamics among electroweak gauge bosons

✳ An echo of extra spacetime dimensions

Why will it matter?

Imagine a world without a symmetry-breaking (Higgs) mechanism at the electroweak scale

Without a Higgs mechanism …

Electron and quarks would have no mass

QCD would confine quarks into protons, etc.

Nucleon mass little changed

Surprise: QCD would hide EW symmetry,

give tiny masses to W, Z

Massless electron: atoms lose integrity

No atoms means no chemistry, no stable composite structures like liquids, solids, …

arXiv:0901.3958

Electroweak Questions for the LHC

- What hides electroweak symmetry: a Higgs boson, or new strong dynamics?
- If a Higgs boson: one or several?
- Elementary or composite?
- Is the Higgs boson indeed light, as anticipated by the global fits to EW precision measurements?
- Does H only give masses to $W^{\pm}$ and Z^{0}, or also to fermions? (Infer $t\bar{t}H$ from production)
- Are the branching fractions for $f\bar{f}$ decays in accord with the standard model?

If all this: what sets the fermion masses and mixings?

Problems of the Standard Model

The Problem of Identity

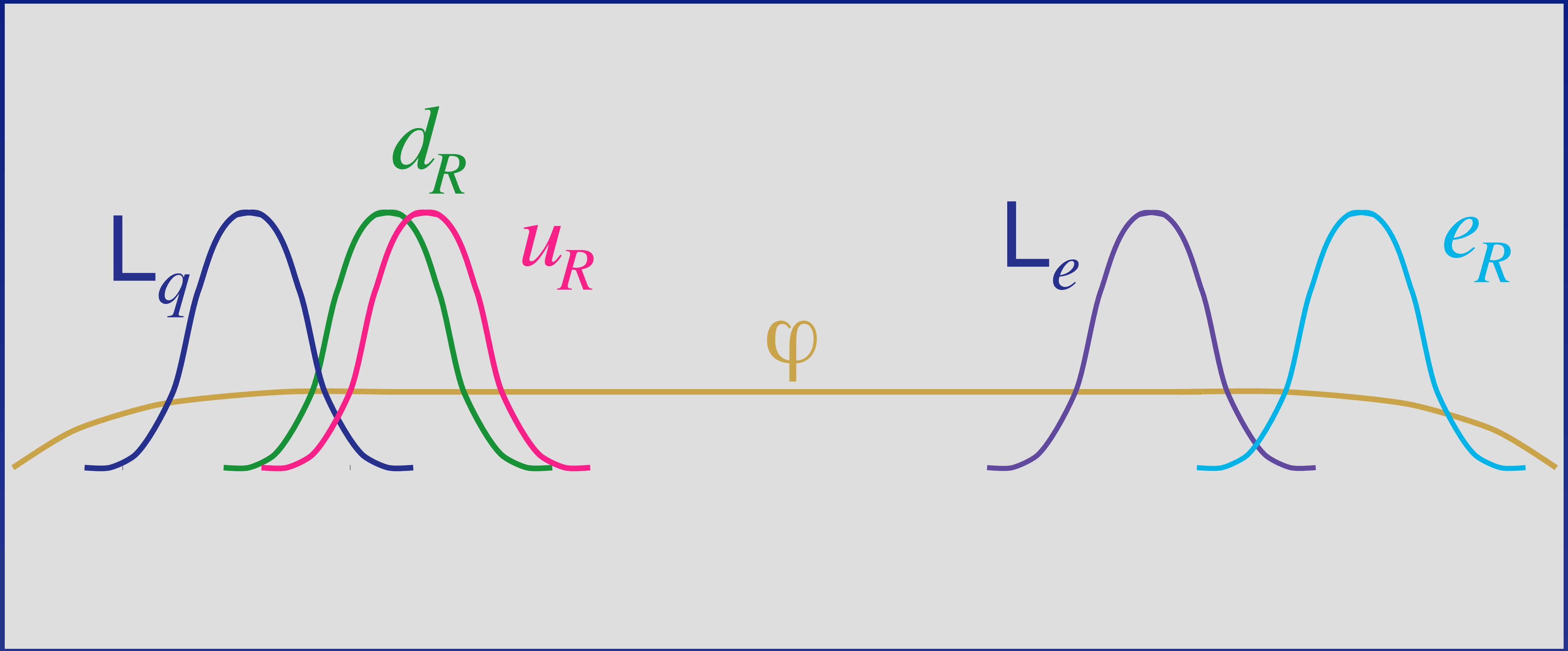
What makes a top quark a top quark,
an electron an electron, a neutrino a neutrino?

Why three families?

Parameters of the Standard Model

3	coupling parameters $\alpha_s, \alpha_{\text{em}}, \sin^2\theta_W$
2	parameters of the Higgs potential
1	vacuum phase (QCD)
6	quark masses
3	quark mixing angles
1	CP-violating phase
3	charged-lepton masses
3	neutrino masses
3	leptonic mixing angles
1	leptonic CP-violating phase (+ Majorana . . .)
26^+	arbitrary parameters

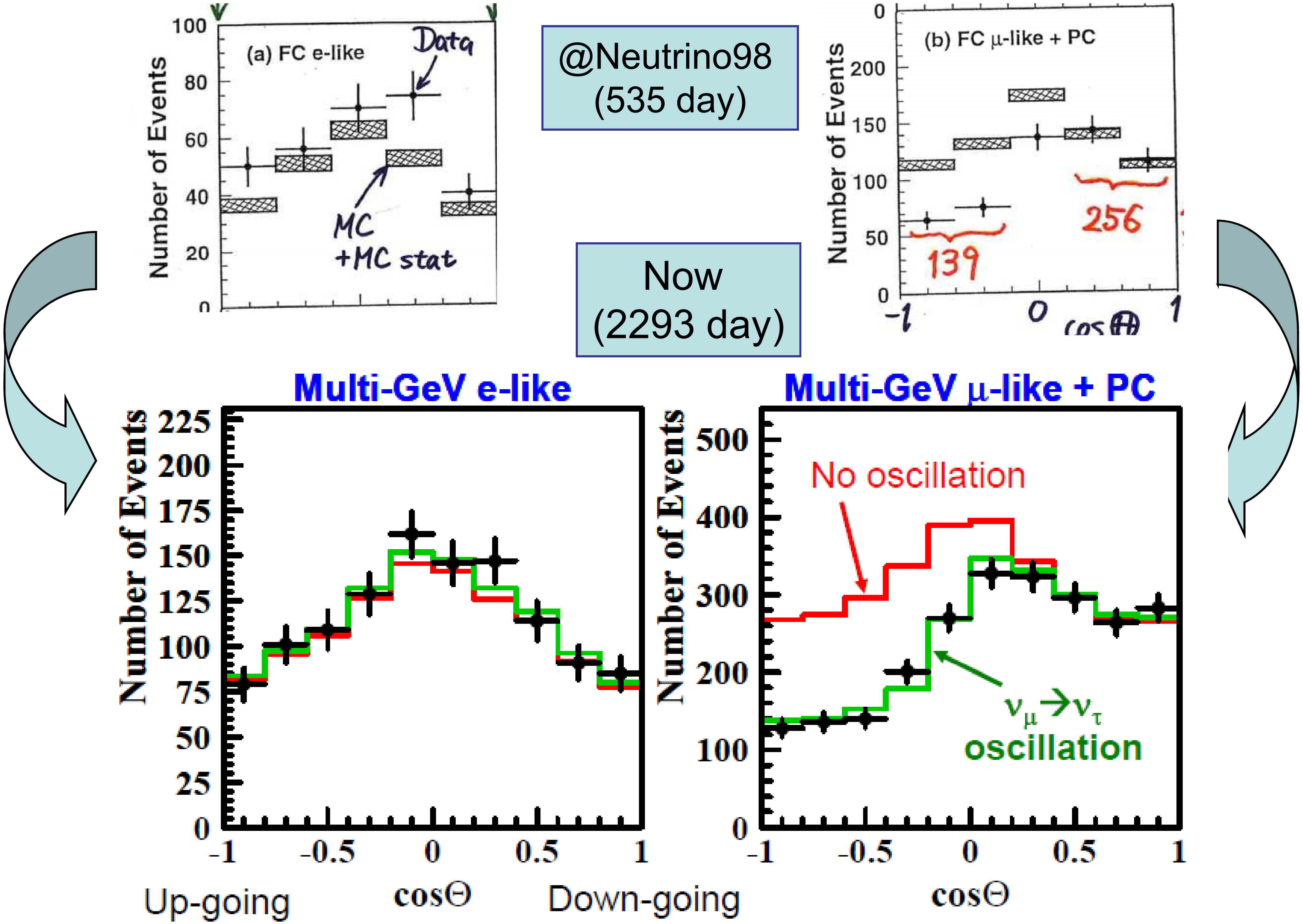
Might extra dimensions explain the range of fermion masses?



Fermions ride separate tracks in 5th dimension

Small offsets in x_4: exponential differences in masses

SuperK Atmospheric Neutrinos

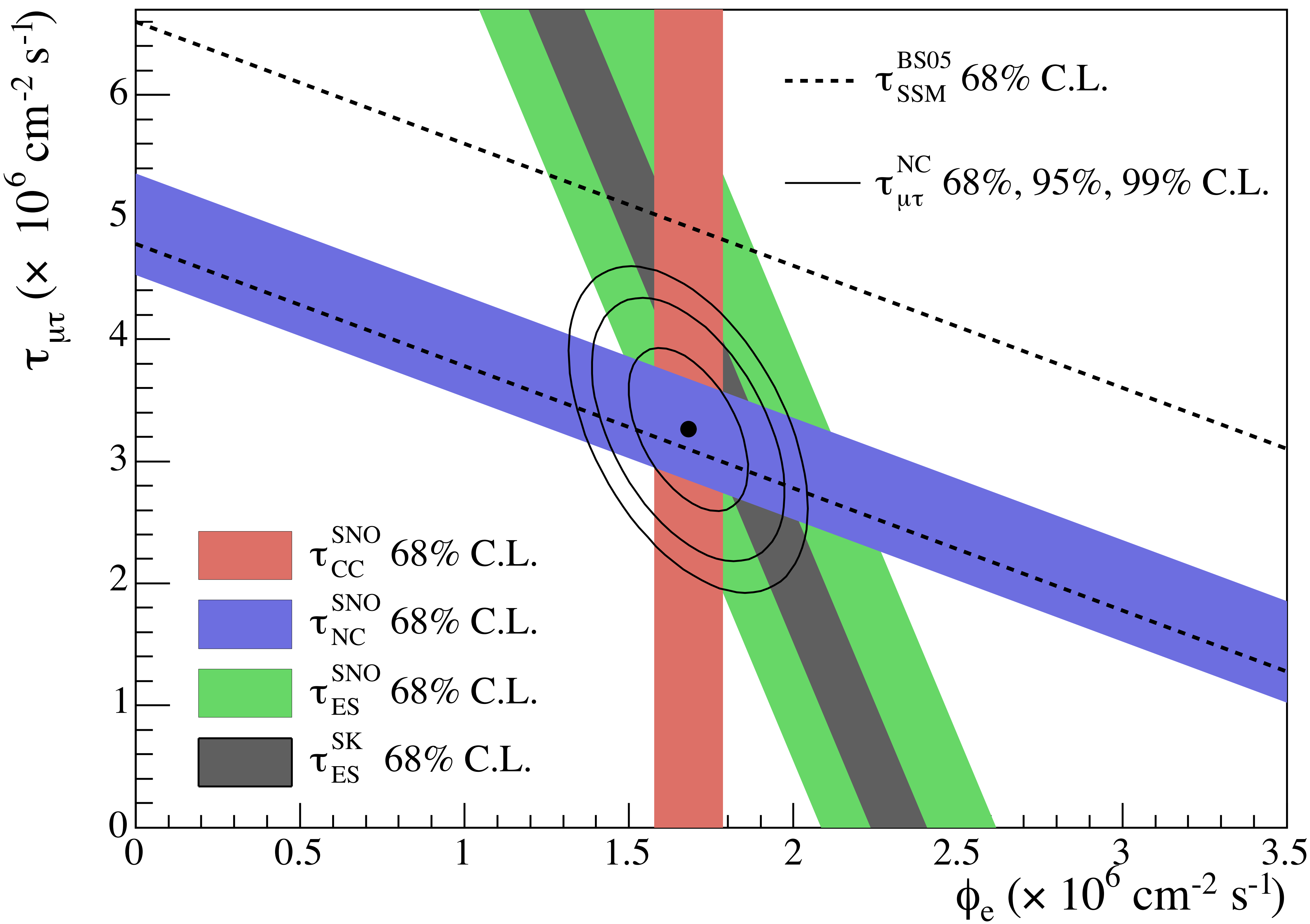


Downward ν travel 15 km, upward ν up to 13 000 km

Solar neutrino observations: SuperK & SNO

Total flux agrees with solar model, but only 30% arrive as ν_e

Solar ν emerge as ν_2



KATRIN aims at 0.2 eV

$$^{3}\mathrm{H} \rightarrow \; ^{3}\mathrm{He}\, e^{-} \bar{\nu}$$

Will the fermion masses and mixings reveal symmetries or dynamics or principles?

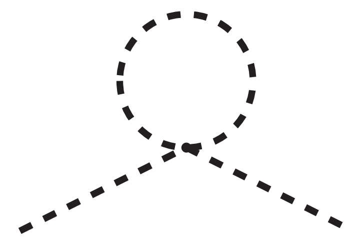
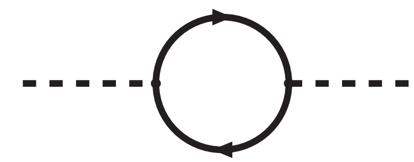
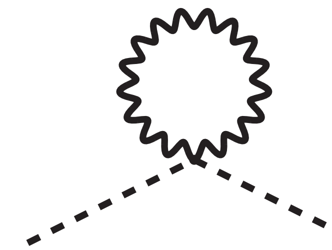
Some questions now seem to us the wrong questions:
Kepler's obsession – Why six planets in those orbits?

Landscape interpretation as environmental parameters

Might still hope to find equivalent of Kepler's Laws!

The Hierarchy Problem

Evolution of the Higgs-boson mass

$$M_H^2(p^2) = M_H^2(\Lambda^2) +$$  **+**  **+** 

quantum corrections from particles with $J = 0, \frac{1}{2}, 1$

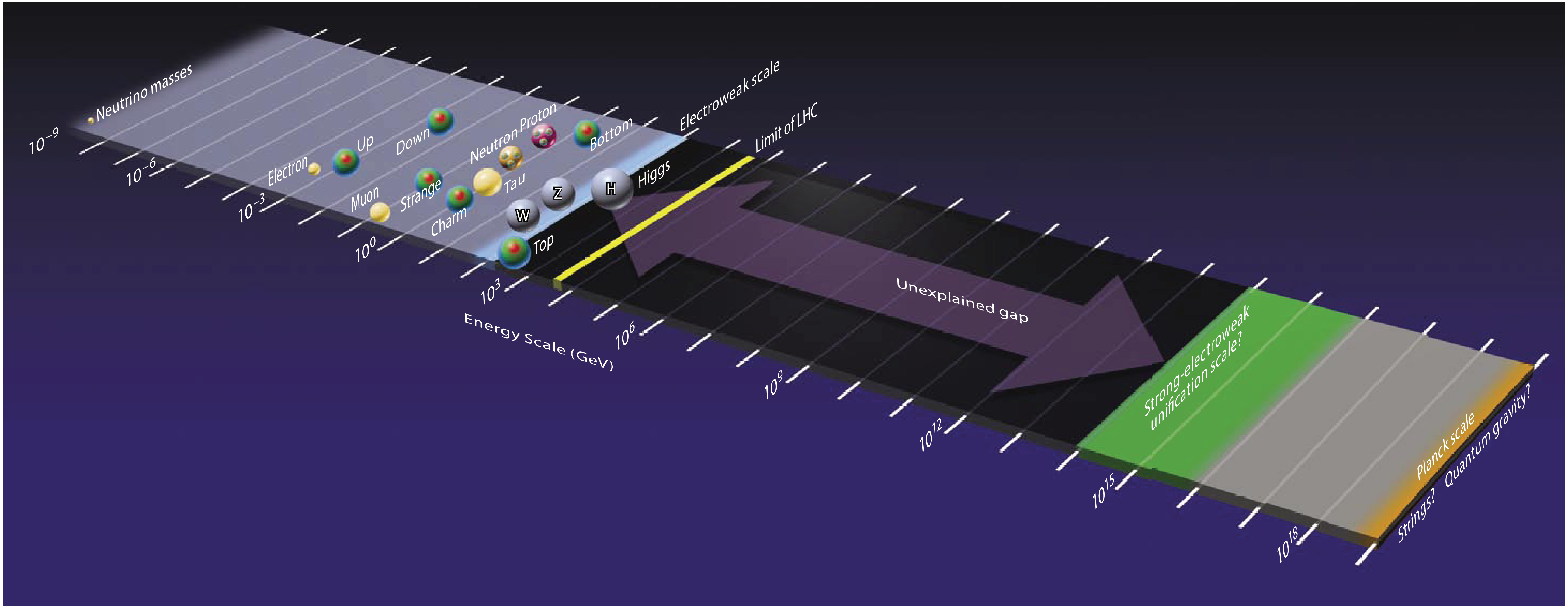
Potential divergences:

$$M_H^2(p^2) = M_H^2(\Lambda^2) + \mathcal{C}g^2 \int_{p^2}^{\Lambda^2} dk^2 + \cdots \ ,$$

Λ: naturally large, $\sim M_{\text{Planck}}$ or $\sim U \approx 10^{15-16}$ GeV

How to control quantum corrections?

The Hierarchy Problem



How to keep the distant scales from mixing in the face of quantum corrections? *OR*
How to stabilize the mass of the Higgs boson on the electroweak scale? *OR*
Why is the electroweak scale small?

The Hierarchy Problem

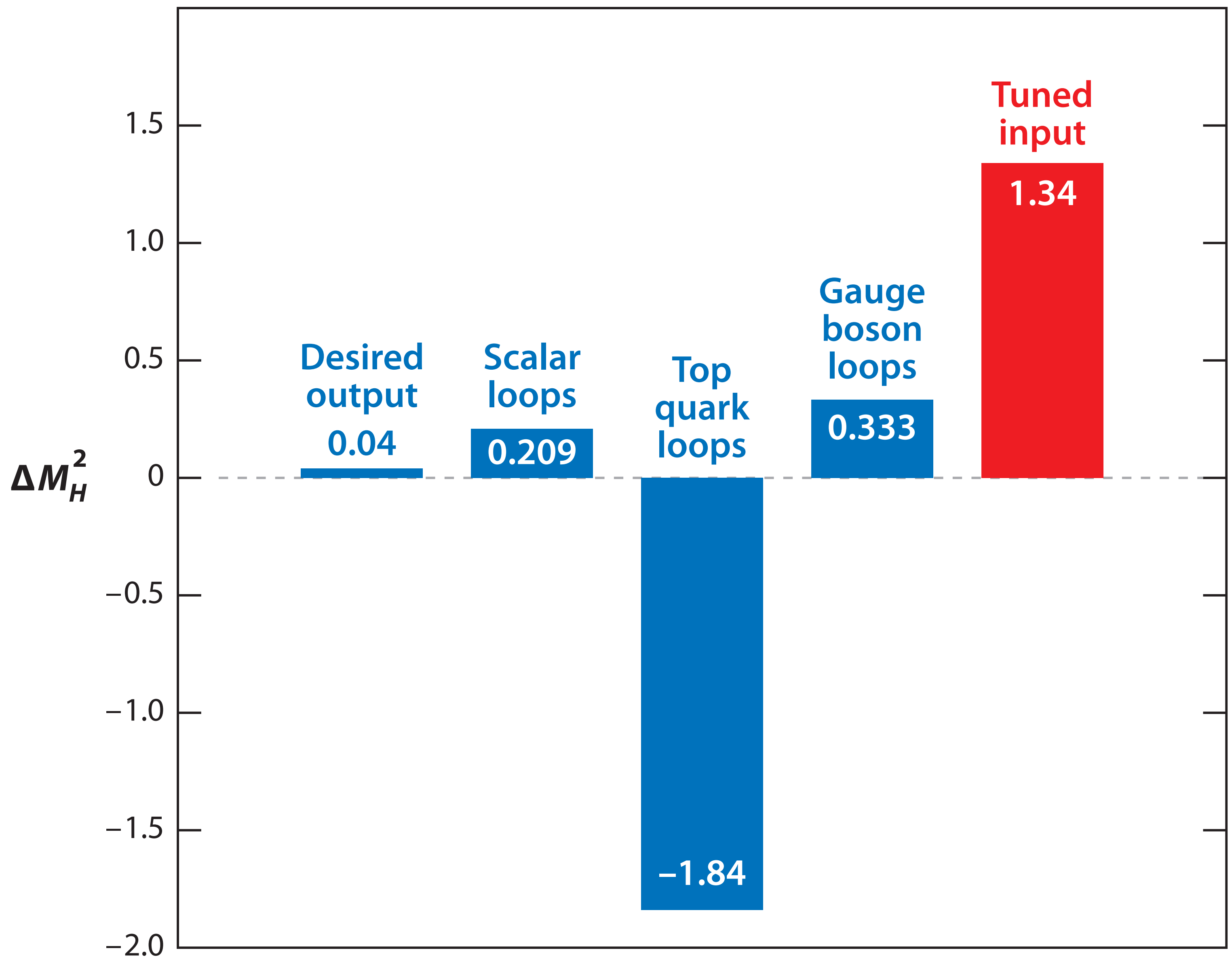
Possible paths

- Fine tuning
- A new symmetry (supersymmetry)
  fermion, boson loops contribute with opposite sign
- Composite "Higgs boson" (technicolor . . .)
  form factor damps integrand
- Little Higgs models, etc.
- Low-scale gravity (shortens range of integration)

$\boxed{\text{All but first require new physics near the TeV scale}}$

A Delicate Balance . . . even for $\Lambda = 5$ TeV

$$\delta M_H^2 = \frac{G_F \Lambda^2}{4\pi^2\sqrt{2}}(6M_W^2 + 3M_Z^2 + M_H^2 - 12m_t^2)$$



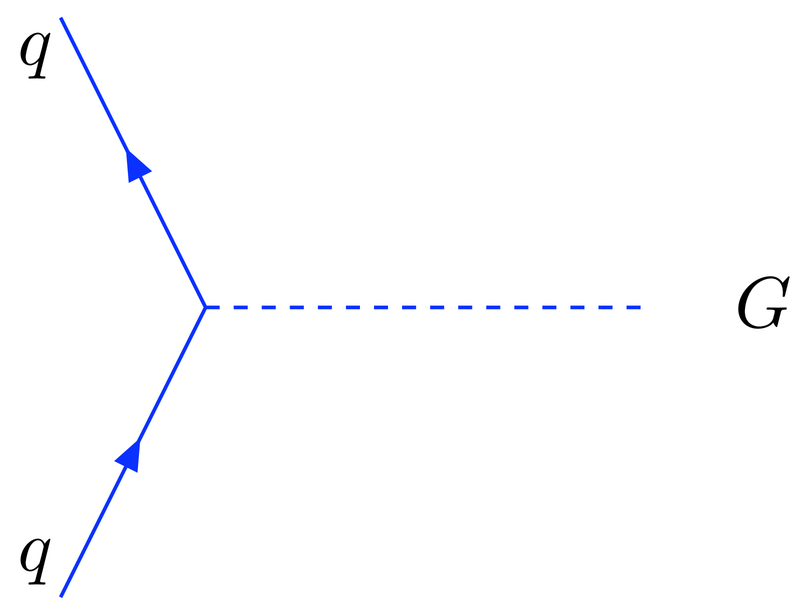
Light Higgs + no new physics: LEP Paradox

Why is empty space so nearly massless?

Natural to neglect gravity in particle physics . . .

Gravitational *ep* interaction $\approx 10^{-41} \times$ EM

$$G_{\text{Newton}}\ \textit{small} \iff M_{\text{Planck}} = \left(\frac{\hbar c}{G_{\text{Newton}}}\right)^{\frac{1}{2}} \approx 1.22 \times 10^{19}\ \text{GeV}\ \textit{large}$$



$$\sim \frac{E}{M_{\text{Planck}}}$$

300 years after Newton: Why **is** gravity weak?

But gravity is not always negligible . . .

The vacuum energy problem

$$\text{Higgs potential } V(\varphi^\dagger\varphi) = \mu^2(\varphi^\dagger\varphi) + |\lambda|\,(\varphi^\dagger\varphi)^2$$

At the minimum,

$$V(\langle\varphi^\dagger\varphi\rangle_0) = \frac{\mu^2 v^2}{4} = -\frac{|\lambda|\, v^4}{4} < 0.$$

$$\text{Identify } M_H^2 = -2\mu^2$$

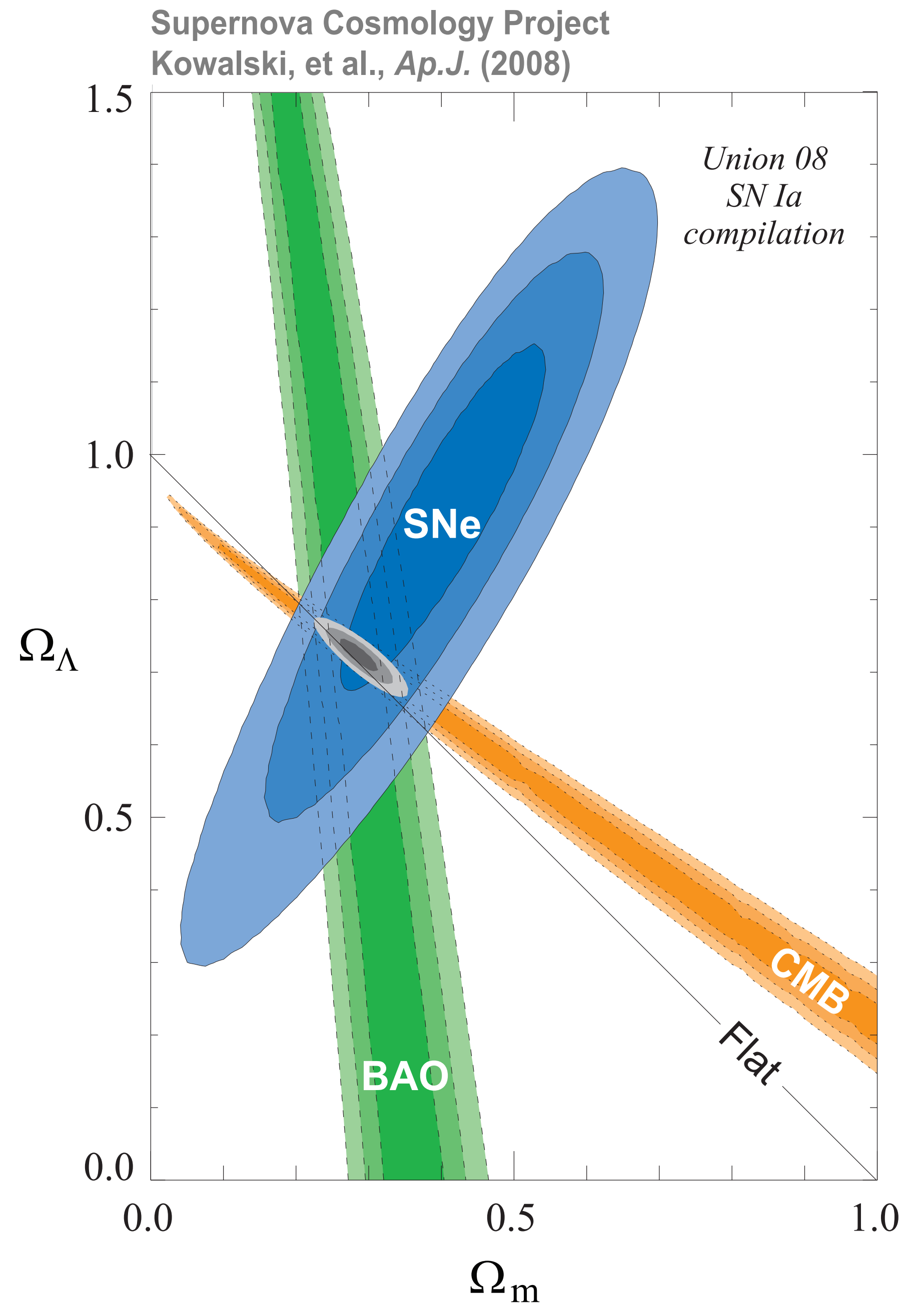
$V \neq 0$ contributes position-independent vacuum energy density

$$\boxed{\varrho_H \equiv \frac{M_H^2 v^2}{8} \geq 10^8\ \text{GeV}^4} \quad \approx 10^{24}\ \text{g cm}^{-3}$$

Adding vacuum energy density $\varrho_{\text{vac}} \Leftrightarrow$ adding cosmological constant Λ to Einstein's equation

$$R_{\mu\nu} - \tfrac{1}{2}Rg_{\mu\nu} = \frac{8\pi G_{\text{N}}}{c^4}T_{\mu\nu} + \Lambda g_{\mu\nu} \qquad \Lambda = \frac{8\pi G_{\text{N}}}{c^4}\varrho_{\text{vac}}$$

Observed $\varrho_{\text{vac}} \lesssim 10^{-46}\ \text{GeV}^4$

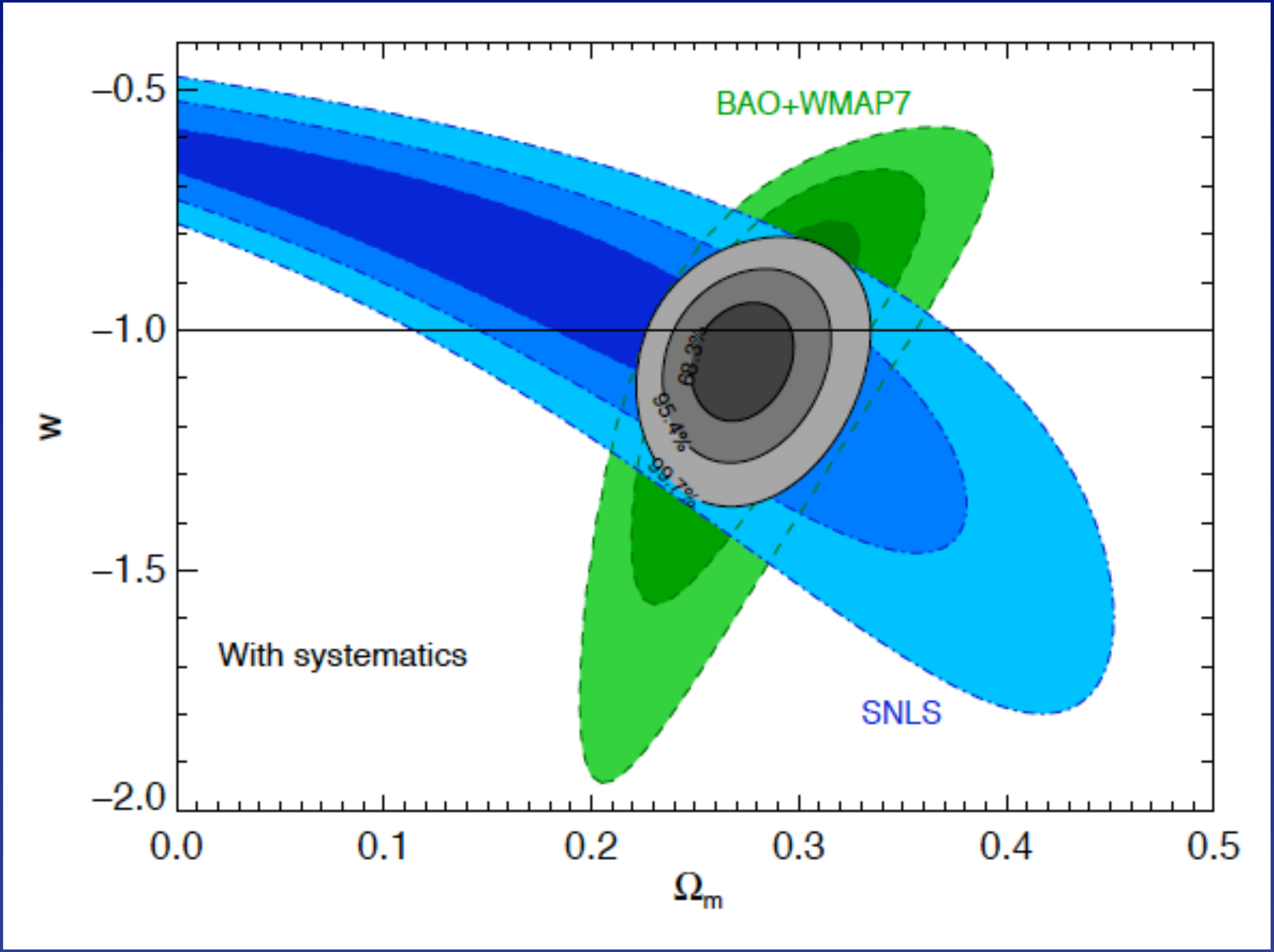


$\varrho_H \gtrsim 10^8\ \text{GeV}^4$: mismatch by 10^{54}

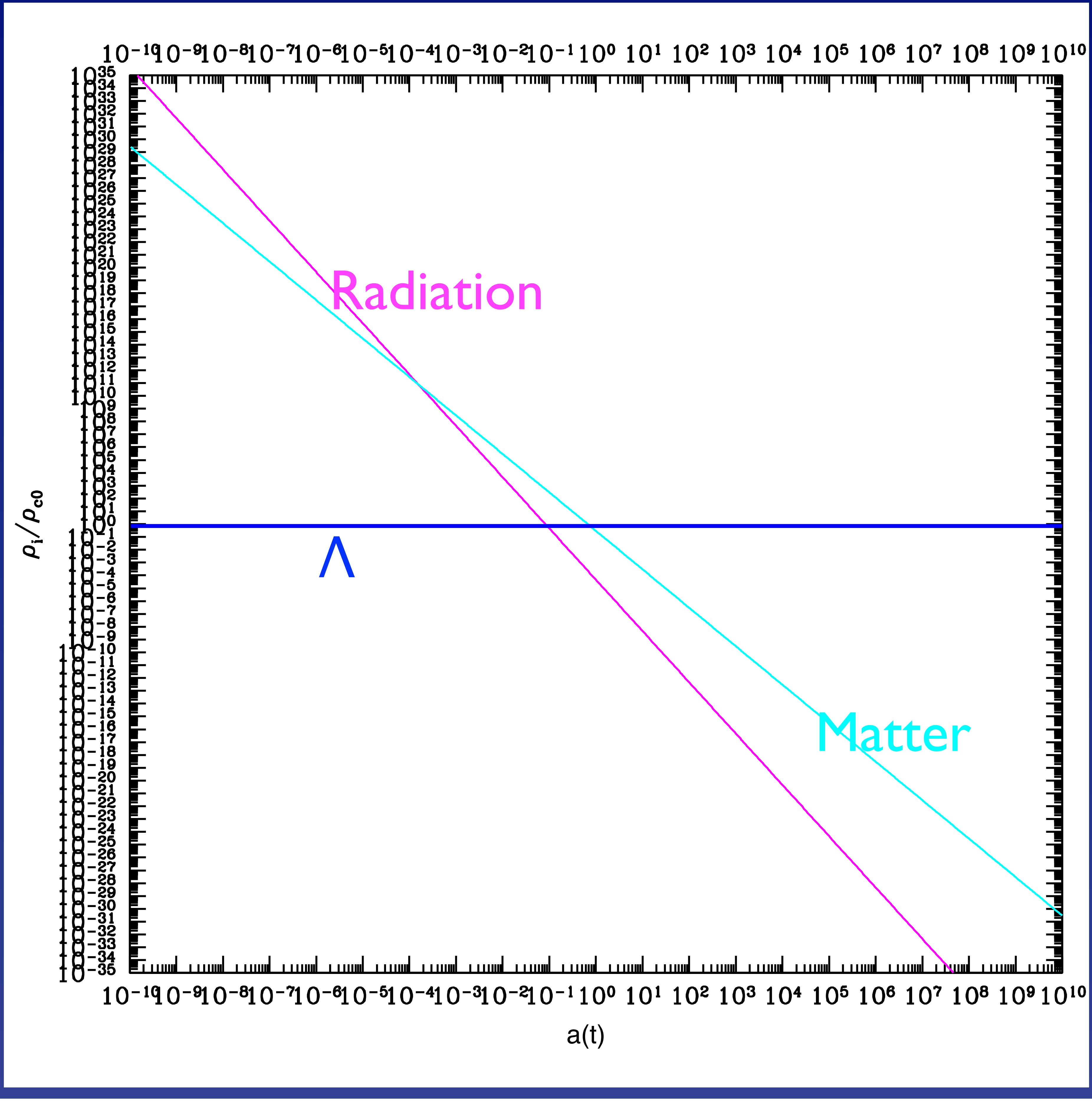
A chronic dull headache for thirty years . . .

Accelerated Expansion Consistent with Cosmo. Constant

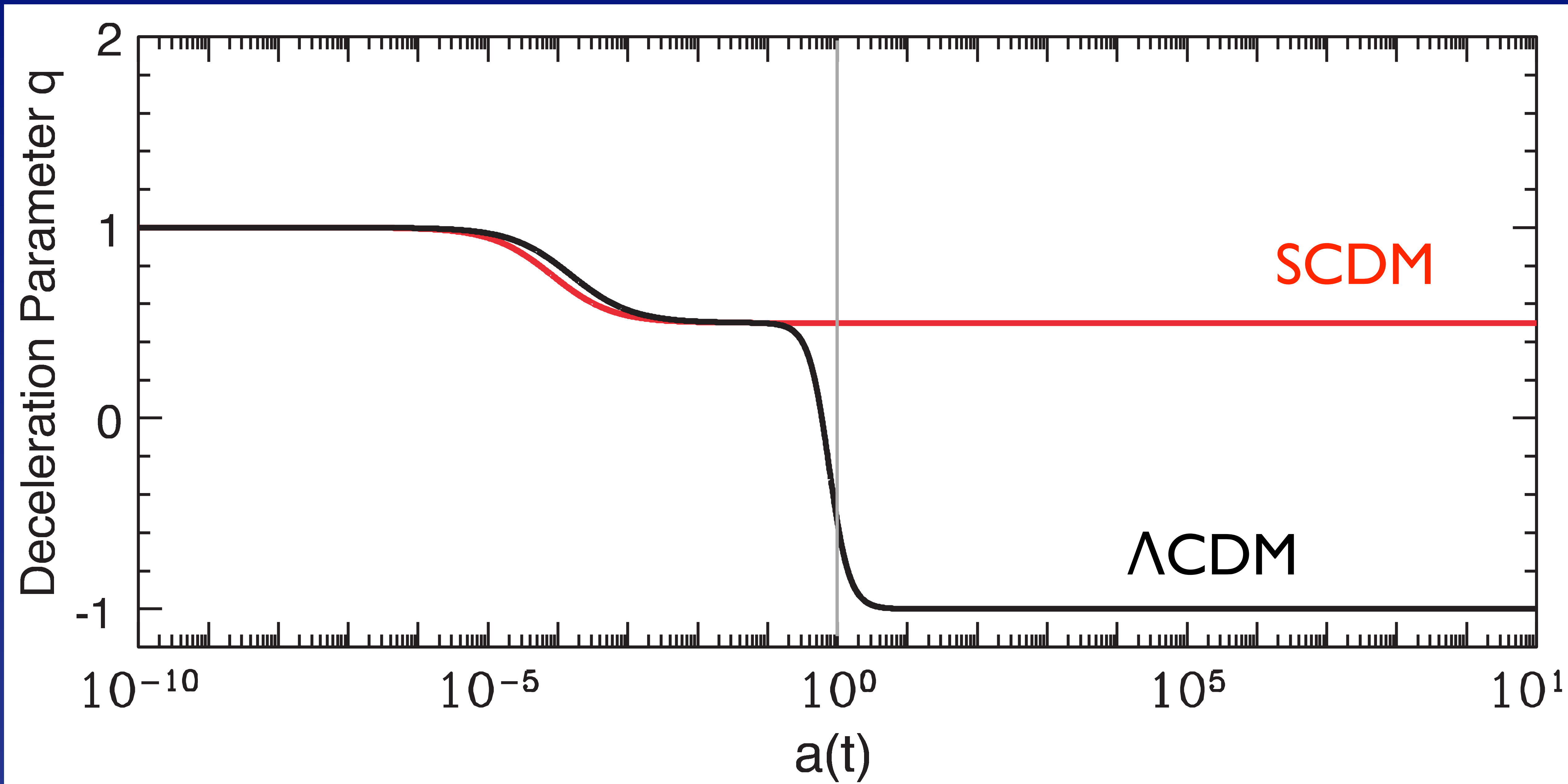
$w = p/\rho$



Composition of the Universe (?)

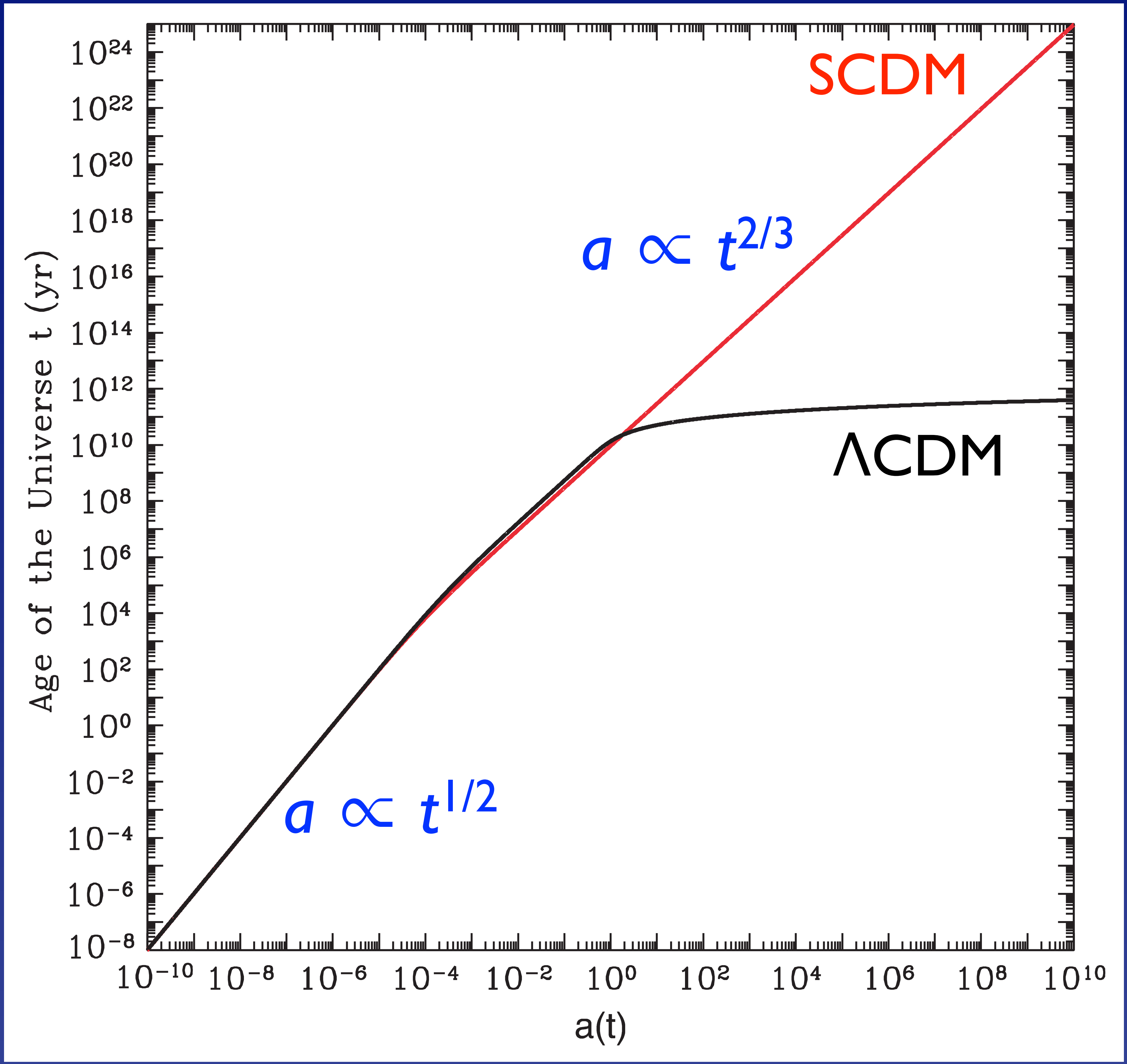


Accelerating expansion has remarkable implications



$$q \equiv -\frac{1}{H^2}\,\frac{\ddot{R}}{R} = \frac{\Lambda}{3H^2} - \frac{4\pi G_{\mathrm{N}}}{3H^2}\,(\rho + 3p)$$

Accelerating expansion has remarkable implications



Lacunae

(Massive Neutrinos)
Dark Matter Candidates
Baryon-Antibaryon Asymmetry
Charge Quantization
Absence of Gravity

More Electroweak Questions for the LHC

- What is the agent that hides electroweak symmetry?
- Is the “Higgs boson” elementary or composite? How does the Higgs boson interact with itself? What triggers electroweak symmetry breaking?
- New physics in pattern of Higgs-boson decays?
- Will (unexpected or rare) decays of H reveal new kinds of matter?
- What would discovery of > 1 Higgs boson imply?
- What stabilizes M_H below 1 TeV?
- How can a light H coexist with absence of new phenomena?
- Is EWSB related to gravity through extra spacetime dimensions?

More Electroweak Questions for the LHC$^{\text{bis}}$

- Is EWSB emergent, connected with strong dynamics?
- If new strong dynamics, how can we diagnose? What takes place of H?
- Does the Higgs boson give mass to fermions, or only to the weak bosons? What sets the masses and mixings of the quarks and leptons?
- Does the different behavior of left-handed and right-handed fermions with respect to charged-current weak interactions reflect a fundamental asymmetry in the laws of nature?

More Electroweak Questions for the LHC$^{\text{ter}}$

- What will be the next symmetry recognized in Nature? Is Nature supersymmetric? Is the electroweak theory part of some larger edifice?
- Are there additional generations of quarks and leptons?
- What resolves the vacuum energy problem?
- What lessons does electroweak symmetry breaking hold for unified theories of the strong, weak, and electromagnetic interactions?

How are we prisoners of conventional thinking?

?

Great Lesson of XXth Century Science

The human scale of space & time is not privileged for understanding Nature . . . and may even be disadvantaged

Thank you!